# Domestic Sustainable and Low Energy Design in Hot Climatic Regions

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## Abstract

Low energy building methods, and the corresponding economic and environmental aspects, are an important area of consideration in many developed countries. Saudi Arabia characterized by its hot climates and geographical location in a global region renowned for its high energy consumption and carbon emission rates. Consequently, this research aims to foster the development of low energy housing in Saudi Arabia and establish a low carbon domestic design framework for Saudi Arabia that takes into account the local climatic conditions, context and socio-cultural challenges. In order to fulfil the above stated aims, this research establishes a definition system for low energy consumption in kWh/m² for the Saudi Arabian climate.

To achieve the aims stated above, a comprehensive, four stage study has been performed. This investigation has attempted to: (a) identify factors resulting in high energy consumption in domestic buildings in Saudi Arabia; (b) identify the weaknesses of housing design in terms of architectural layouts and mass, house envelope design and construction materials used, and on-site renewable energy strategies; (c) establish and develop a low carbon domestic design framework that supports architects, civil engineers and building professionals in the design of sustainable homes for the Saudi Arabian climate, context and cultural requirements; and (d) propose three different, viable housing prototypes employing the established framework, thereby validating that framework through the identification of their energy consumption levels.

Each stage of this research utilizes a specific methodology: public survey analysis; site visits and modeling analysis; expert consultation, using the Delphi technique approach; and the validation analysis approach. This study contributes to the body of knowledge within this field by offering a low carbon domestic framework for the design of low energy homes in Saudi Arabia. These findings are broadly applicable to other regions with similar climatic conditions and cultural requirements, such as those in the Middle East and GCC countries. The findings suggest that an energy reduction of up to 71.6 % is possible. Therefore, the system for low energy consumption level standards is suggested as a range between 77 kWh/m² and 98 kWh/m². The comprehensive economic and environmental benefits of these reductions have been analysed and benchmarked against the current situation in selected developed countries.

# List Of Publications

***Publications in leading Journals:***

Aldossary N, Rezgui Y, Kwan AS, Domestic energy consumption patterns in a hot and arid climate: A multiple-case study analysis, *Renewable Energy* , 62 (2014) 369-378 ISSN 0960-1481 10.1016/j.renene.2013.07.042

Aldossary N, Rezgui Y, Kwan AS, Domestic energy consumption patterns in a hot and humid climate: A multiple-case study analysis, *Applied Energy* , 114 (2014) 353-365 ISSN 0306-2619 10.1016/j.apenergy.2013.09.061

Aldossary N, Rezgui Y, Kwan AS, An investigation into factors influencing domestic energy consumption in an energy subsidized developing economy, *Habitat International,* 47 (2015), 41-51 ISSN: 0197-3975 http://dx.doi.org/10.1016/j.habitatint.2015.01.002

Aldossary N, Rezgui Y, Kwan AS, Consensus-based Low Carbon Domestic Design Framework for Sustainable Homes, Renewable & Sustainable Energy Review, ISSN: 1364-0321

***Published Conference Papers***

***International conference in USA:***

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# Chapter 1 : Introduction

Building performance has been recognised, over the past two decades, as a key contributor to the negative environmental impact of excessive fossil fuels use. More specifically, buildings are responsible for approximately 70% of sulphur oxides and 50% of the $CO_2$ emissions released into the atmosphere (C. Ghiaus, 2004). The building sector consumes 40% of the world's energy, 16% of the world's fresh water, and 25% of the timber taken from forests (C. Ghiaus, 2004). In response to these statistics there has been considerable interest in the developed world, in recent years, towards the production of sustainable building to promote protection of the environment. This entails addressing energy and environmental considerations, by producing climate-responsive designs that succeed in delivering building comfort through utilisation of natural energy sources and systems; such designs would account for interactions among the dynamic conditions affecting each building's unique environment (Hyde, 2000).

With the increasing evidence that climate change and global warming are the result of anthropogenic discharges of greenhouse gas, it has become essential to implement urgent steps to prevent hazardous implications for future generations (Taleb and Sharples, 2011). Given the above statistics, the building sector has an instrumental role in this effort. The key factors that have a significant effect on construction and its maintainability include economy, climate, accessibility to technology and materials, as well as the socio-cultural context (Singh et al., 2009). Furthermore as climate differs in various regions, suitable architectural solutions for particular construction settings have to be devised (Singh et al., 2009). Vernacular architecture, built by local people often offers environmentally conscious architectural solutions while responding to socio-cultural requirements. (Engin et al., 2007) It could therefore be employed in today's architectural practice as a source of inspiration. Energy effective construction has the potential to decrease $CO_2$ emissions by 60% or more, which translates to 1.35 billion tonnes of $CO_2$ emissions (Tzikopoulos et al., 2005). Thus, climate reactive construction is currently a requirement, and not an alternative, for power saving and carbon discharge decreasing (Tzikopoulos et al., 2005). Setting standards and conventions comprises a basic foundation for maintainable solutions (Saleh, 2004).

This chapter provides an overview of the importance of reducing energy consumption in buildings and the manner in which developed countries have determined future targets. In addition, this section presents a statement of the problem in Saudi Arabia in terms of energy consumption in domestic buildings. The examination of the Saudi Arabian context led to the formulation of the research questions as well as the aims and objectives of this research. This chapter presents an outline of these aspects of my research along with brief references to the encountered challenges, its contribution to the body of knowledge and a summary of the thesis' chapters. The following section provides an overview of the research structure, research limitations and contribution to body of knowledge.

## 1.1 Energy Consumption In Domestic Buildings: Worldwide Issues

Energy consumption patterns depend on local climate conditions, the culture of the citizens and the policies of the country. It is not necessarily efficient to use solutions that help to reduce energy consumption in buildings in one particular location for construction in another location with a different culture, climate conditions, availability of raw materials, and a different economy and policies. Many developed countries are addressing energy conservation in the building sector in general and in residential buildings in particular. Some of these countries have established official standards defining the band of energy consumption in domestic buildings in kWh/m² as low or very low, based on the local climate conditions, culture, policies and occupants` needs. Low energy homes and energy conservation in buildings remain targets for developed countries to address in order to achieve sustainable environmental and economic development.

'Low carbon energy buildings', 'eco-houses' and 'green buildings', are terms commonly used by both engineers and architects. Low carbon energy buildings reflect design choices intended to reduce the impact of construction on the environment. It is possible for low energy buildings to reduce certain operational building costs by as much as 80% through application of integrated design. Europe now has 20,000 low energy built houses (EU, 2009). Low energy buildings are buildings with a better energy performance when compared with standard ones (EU, 2009). This type of building typically utilises high performance insulation, energy efficient glazing and low energy consumption technology in heating and cooling systems (EU, 2009). Moreover, a low energy building may use solar energy and technologies for hot water heat recycling.

The EU is fully engaged in implementing staged energy and $CO_2$ reduction targets (Schade et al., 2013, Košir et al., 2014). In 2008, a survey across Europe identified seventeen different terms in use to describe low energy domestic houses (EU, 2009). These include: passive house, low energy house, high performance house, zero energy house (McLeod et al., 2012), energy saving house, energy positive house, and 3-litre house. The literature on this subject also uses the terms ultra-low energy house, eco-house and green house (EU, 2009).

At present, seven European Member States have adopted a working definition of a low energy house. These definitions are most often applied to new houses, but also cover existing houses, and can usually apply to both residential and non-residential buildings. The required reduction in energy consumption normally ranges from 30% to 50%, depending on the particular sustainability measures incorporated in the proposed design. This generally corresponds to an annual demand for energy ranging from 40 to 60 kWh/m² in central Europe. Terms have been introduced in some European countries (for example MINERGIE in Switzerland, and Effinergie in France) to help occupants identify the national standard for low energy houses (EU, 2009).

In this context, it is difficult to define exactly what can be termed a low energy House given the variety of regulations and climates across Europe and beyond (including US) (EU, 2009). In Austria and Germany, for example, the energy consumption of a low energy home should be below 60-40 kWh/m² per year, while in France the average annual consumption must be lower than 50 kWh/m². Still, some countries like England and Wales are even more ambitious aiming for zero carbon buildings by 2016. Moreover, what is considered a low energy development in one country may not meet local definitions in another (EU, 2009). An example of this is the Energy Star label in the US, which is awarded to Houses that use 15% less energy than what regulations call for in typical new homes (EU, 2009).

## 1.2 Statement Of The Problem In Saudi Arabia

Saudi Arabia is a rich oil producing country, exporting energy in the form of oil and with an economy based on the oil industry. It is also a country characterised by high energy consumption and $CO_2$ emission rates. The hot climate in the region and the corresponding operation of air conditioning systems explains to a large extend the high levels of energy consumption (Taleb and Sharples, 2011). The future projections, moreover, depict an even more alarming image for the country. Energy consumption in the Kingdom of Saudi Arabia, in the form of electricity, has increased sharply over the last two decades (Al-Ajlan et al., 2006). This increase is due to the rapid development of the economy in the absence of energy conservation policies. Specifically, peak load reached approximately 24GW in 2001, which was about 25 times that of 1975, and it is expected to reach 60GW by 2023 (Al-Ajlan et al., 2006). In economic terms, the total investment required in order to meet this demand could exceed 90 billion USA Dollars (Al-Ajlan et al., 2006).

This large consumption of electrical energy for buildings also represents a major potential for reducing energy consumption (Fasiuddin and Budaiwi, 2011). Yet, an energy conscious attitude continues to be virtually absent in the developing world, and this also pertains to Saudi Arabia. For example, official sources such as the Saudi Arabia Ministry of Electricity have stated that over half (51.1%) of electricity is consumed by the domestic sector, (Electricity, 2010) and all newly constructed Saudi residential buildings depend on air conditioning for interior cooling.

Although natural energy resources, such as solar radiation, are abundant in Saudi Arabia (Rehman et al., 2007), the bulk of electricity is currently generated by burning fossil fuels (Alnatheer, 2006, M, 2002). The application of technology required to utilise sustainable energy resources, such as solar photovoltaic (PV) cells, is rare in Saudi Arabia (Al-Saleh, 2009, Taleb and Pitts, 2009). This is due, in part, to the fact that currently there are no regulations or compulsory building codes requiring builders to incorporate energy efficiency principles in their architecture. Yet the scientific community has already established a clear code of standards as one of the more cost-efficient methods by which to promote the spread of sustainable practices. The aim of such a code would be to target effective reductions in household energy use and water consumption (Chwieduk, 2003, Taleb and Sharples, 2011).

The architectural practices together with the rapid population growth, the economic development in Saudi Arabia, and the consequent rapid increase in energy demand in the form of electricity, has taken place over the last 25 years (Al-Ajlan et al., 2006). According to the Saudi Arabia Central Department of Statistics and Information, the

population of Saudi Arabia reached 29,994,272 in 2013 and is likely to reach 37,610,985 by 2025. This rapid increase will result in further energy demands to operate new domestic buildings, with a consequential economic and environmental cost.
According to the Saudi Arabia Ministry of Electricity (Electricity, 2010), the energy sold to the residential sector in Saudi Arabia was about 108,627 GWH in 2010 which was 51% of the total sold energy for all sectors and this quantity is increasing annually by 6.4%. The quantity of oil needed to generate electricity during 2010 can be estimated as follows:

- *One barrel of petroleum can generate 533 kWh,*
- *therefore 108,627 GWh of electricity consumes 203,803,002 barrels of petroleum annually to generate energy in the form of electricity for the residential sector*

These figures demonstrate the extent to which energy generation by burning fossil fuels depletes non renewable natural resources and pollutes the environment through high levels of $CO_2$ emissions. On the other hand, these figures also demonstrate a significant opportunity to invest the proceeds from oil to reduce energy consumption in the residential sector and to develop a sustainable industry in the hot climate of Saudi Arabia. About 214,433 residential units are to be built in the future under the management of the Ministry of Housing (Ministry of Housing, 2014). These residential units will require significant energy, in the form of electricity, to operate. An environmentally conscious approach to their design and operation could have enormous economic and environmental benefits.

In view of the high energy consumption by the residential sector in Saudi Arabia, serious steps are urgently needed in order to reduce energy consumption, increase income by selling the oil for other purposes, and lower $CO_2$ emission rates. Such steps should be formalised in a framework specifically designed for the environment and culture of Saudi Arabia. This framework, then, would provide architectural solutions that reduce energy demand and general guidelines for the design of sustainable homes for the future. Many developed countries have dealt with energy saving through the development of sustainable energy consumption codes and established energy consumption standards based on local climate conditions and citizens' needs; such codes are absent in Saudi Arabia and are essential to control energy consumption and conserve fossil fuels for future needs (Taleb and Sharples, 2011, Chwieduk, 2003)

## 1.3 Research Hypothesis And Questions

The hypothesis of this research is that, the concept and principles of low energy buildings can be profitably adopted within the Saudi Arabian climatic and cultural context. They can lead to energy conservation and to huge environmental and economic benefits for housing stock across Saudi Arabia. Low energy housing standards, furthermore,can manage and control the energy consumption in the domestic sector of Saudi Arabia. Hence; a number of research questions have been established as a basis upon which to design a research plan (methodology). The research questions are as follows:

**Research Question one – RQ1)** What is the average energy consumption in typical existing homes in Saudi Arabia and what level of $CO_2$ emissions result from operating typical homes in Saudi Arabia?

**Research Question two – RQ2)** What are the design weaknesses related to the architectural design (form) and house envelope design (fabric) that cause high energy consumption in existing domestic buildings in Saudi Arabia?

**Research Question three – RQ3)** What are the factors impacting on energy consumption and what are the cultural factors that affect house design in Saudi Arabia and result in high energy consumption?

**Research Question four – RQ4)** What is the public perception of sustainable, low energy buildings in Saudi Arabia and the socio-cultural blockers that inhibit sustainable, low energy homes in Saudi Arabia?

**Research Question five – RQ5)** What is the level of energy efficiency (based on energy efficient design) that can be achieved for housing in Saudi Arabia when compared with developed countries?

**Research Question six - RQ6)** How can the construction of existing homes be altered and retrofitted in order to reduce energy consumption?

**Research Question seven - RQ7)** In future, how can sustainable, low energy housing be designed in Saudi Arabia, and which framework methodology can be used? And what economic and environmental benefits can be achieved by establishing low energy housing in Saudi Arabia?

## 1.4 Research Aim And Objectives

The main aim of this research is to establish sustainable, low carbon energy domestic buildings in Saudi Arabia taking into account the local hot climate conditions, the architectural context, and the needs and cultural requirements. This can be achieved by (a) developing a framework for the design of low energy homes appropriate to the Saudi Arabian climate, context and culture, and (b) designing and validating sustainable low energy homes for Saudi Arabia. Furthermore, this research aims to establish energy consumption definition standards (in $kWh/m^2$) to control and manage energy conservation in the Saudi Arabian context, in a manner similar to that utilised in some developed countries. More specifically, this research begins with the aim of investigating energy consumption patterns in the Saudi Arabian domestic sector. These findings are then employed in developing a passive, sustainable design framework that could assist architects and civil engineers in designing low energy homes in a hot climate. The second aim of this research is to develop housing prototypes and to measure their energy performance. Through this process, this research seeks to identify a level of energy consumption, in $kWh/m^2$, that is appropriate for the local hot climate, meets the cultural requirements and satisfies occupants' needs. To achieve these aims various other issues related to the Saudi Arabian domestic sector have been considered as well.

These issues include an investigation of occupants' needs across Saudi Arabia and a statistical analysis of energy consumption patterns in current homes. In addition, public perception of sustainable buildings is determined and the socio-cultural blockers that hinder the delivery of low energy homes in Saudi Arabia is identified. These issues need to be considered and analysed in depth to obtain a rich database to address the main aims of the research. The principles of sustainable development are applied in order to meet this aim. In this regard, establishing low energy buildings in Saudi Arabia is believed to be the best solution to reduce energy consumption, protect the environment from $CO_2$ emissions and achieve sustainability in the domestic sector. Thus, with regard to domestic buildings in Saudi Arabia, a number of objectives are addressed and summarised as follows:

**Objective 1:** Diagnose, analyse and identify factors causing high energy consumption taking into consideration: architectural design style, building size, number of rooms, type of cooling-heating systems in domestic buildings in Saudi Arabia, and the manner in which occupants operate their homes in the country.

**Objective 2:** Analyse, determine public perceptions of sustainable-low energy homes in Saudi Arabia, and assess the willingness of the public to retrofit existing homes to achieve energy conservation.

**Objective 3:** Identify the shortcoming in architectural design (form) and building envelope (fabric) in existing homes that cause high energy consumption in Saudi Arabia and propose solutions that lead to the reduction of energy consumption as far as possible.

**Objective 4:** Review a variety of efficient sustainable building techniques and suggest suitable ones for reducing energy consumption in buildings and using solar radiation as an alternative to the combustion of fossil fuel. Employ appropriate simulation software tools to evaluate and validate the best solutions for building performance in a hot climate.

**Objective 5:** Establish a low carbon domestic design framework for sustainable homes to design sustainable, low energy homes in the Saudi Arabian environment, context and culture.

**Objective 6:** Design and validate sustainable, low energy homes in Saudi Arabia on the basis of the established framework and identify how much can energy consumption be reduced in the residential sector of Saudi Arabia.

**Objective 7:** Establish a system of energy consumption standards (in $kWh/m^2$) for Saudi Arabia on the basis of the outcome of the previous analysis, and benchmark low energy consumption standards for Saudi Arabia against established low energy consumption definition standards in some developed countries.

## 1.5 Contribution To The Body Of Knowledge

The contributions of the present research to the body of knowledge are; (a) establishing a low carbon domestic design framework for sustainable homes; (b) designing low energy domestic buildings and establishing low energy consumption definition standards in $kWh/m^2$ for the Saudi Arabian context; (c) offering solutions and retrofitting strategies for existing homes in Saudi Arabia to reduce energy consumption;

and (d) identifying public perceptions and socio-cultural blockers that inhibit the adoptions of sustainable homes in Saudi Arabia. More specifically:

- **Establishing low carbon domestic design framework for sustainable homes**

This research contributes to the body of knowledge by proposing a framework for the design of low energy homes taking into account the hot climate of Saudi Arabia, as well as the specific cultural requirements of the region. This framework will address such aspects as architectural design (form), house envelope design, construction materials (fabric) and on-site renewable energy devices taking into account local cultural aspects. Architecturally, the strategies will include building design, shading devices, heating, ventilation, air conditioning (HVAC), and building volumetric composition. In terms of house envelope (design and construction materials used), the framework will cover building fabric design strategies, such as the design of external walls, roofs, floors and external glazing. The low carbon domestic design framework will also offer strategies for using renewable energy resources.

Generally, the framework will support architects, civil engineers, building professionals and developers to design low energy buildings in Saudi Arabia on the basis of climate and cultural requirements. Furthermore, the framework will contribute to resolving similar issues in countries with similar climate conditions and cultures, such as the other GCC countries.

- **Designing low energy houses and defining energy consumption standards for Saudi Arabia**

This research proposes designs for low energy domestic buildings appropriate to the Saudi climate and culture, which differ (different designs) from the design models that are currently in use. Furthermore, this research establishes standards for low energy consumption (in $kWh/m^2$) for the Saudi Arabian context and environment, benchmarked against the international energy consumption systems that have been established in some developed countries. Low energy houses in this research were designed, examined and validated using IES-VE simulation software tools. As many developed countries have established definitions standard for energy consumption in $kWh/m^2$, based on their needs and local climates, an energy consumption definition system ($kWh/m^2$) has also been developed, here, for Saudi Arabia on the basis of its climate, culture and occupants` needs. This energy consumption band will control and manage future sustainable, low energy buildings in the design stage, and can be validated and approved using simulation software tools before the construction stage.

- **Retrofitting solutions strategies for existing homes in saudi arabia**

This research also contributes to the body of knowledge by offering strategies for retrofitting existing high energy homes in order to reduce their energy consumption. To prove their efficiency, the proposed solutions were applied to existing homes across Saudi Arabia and the improvement in energy consumption was measured and validated through the use of IES-VE simulation software tools.

- **Overview of housing style, public perception and culture in Saudi Arabia**

This research contributes to the body of knowledge by identifying weaknesses in architectural and building envelope design, as well as construction materials, which cause high energy consumption in domestic buildings in Saudi Arabia. It addresses the socio-cultural blockers that inhibit development of sustainable, low energy homes in Saudi Arabia, and explains how cultural and religious roots affect the architectural design and style of homes in the country. In light of this, an overview of how domestic buildings are designed and constructed is provided and the public perception of sustainable homes in Saudi Arabia is determined. This contributes to the body of knowledge, as future researchers in this field will benefit from the database developed in this research. In addition, this research reflects the culture of Saudi Arabia and also how the people, culture, faith and religion affect their house designs.

## 1.6 Research Challenges

In order to achieve the proposed aim and objectives, the researcher faced multiple challenges. The challenges were overcome with difficultly during the research. The challenges are summarised as follows;

**Firstly,** the research was divided into multiple objectives on the basis of the identified research questions, and in order to achieve the main aim of the study. Consequently, it was necessary to analyse the current situation in the Saudi context by determining the factors leading to high energy consumption in the domestic sector. Hence the methodology and approach had to be multifaceted. As an initial step, it was necessary to assess public perceptions and cultural barriers in order to determine the factors that cause high energy consumption as well as the ability of the public to accept low energy solutions.

On the other hand, it was necessary to identify factors that cause high energy consumption in domestic buildings on a technical level, which cannot be addressed through public investigation and analysis. This task required the employment of another method: it involved visiting different existing domestic buildings, that were already occupied, to investigate the energy consumption patterns technically (using software simulation tools) and to identify design weaknesses in term of architectural design (form), house envelope design (fabric) and on-site renewable energy potential. Moreover, to establish the potential for sustainable, low energy homes in Saudi Arabia, an additional method was used. It comprised discussions with expert consultants in the field to determine and compile the components of a framework of design strategies for low energy homes that meet the needs of the Saudi Arabian climate and cultural requirements. Finally, multiple prototype housing designs were needed in order to assess and analyse the potential decrease of energy consumption resulting from the application of the proposed framework. The energy savings that were calculated in this manner were then classified into low energy standards that were comparable to those used internationally. The challenge here, was that these four different approaches needed to fit the time scale allocated to this research and achieve accurate and comprehensive results.

**Secondly,** Saudi Arabia is a huge country with a variety of hot climates: (a) hot and arid, (b) hot and humid, and (c) hot arid mountainous. Each climatic type requires individual study and separate analysis to insure detailed and accurate results. These different conditions require separated studies to analyse and simulate a number of different domestic buildings across Saudi Arabia on the basis of their local climate. The challenge was that this required significant time to establish the results.

**Thirdly**, based on the previous two challenges, some data sets could not be obtained, because they contain sensitive information; e.g. in some cases the owners of certain houses felt that the divulgence of architectural designs, plans, details of construction materials infringed on their intellectual and property rights. Furthermore, obtaining utility bills from the Ministry of Electricity was difficult for the researcher, because bills show details of clients, including account numbers and payments. Instead this data was collected from the occupants of each property who were provided with the information by the Ministry of Municipality (official plans) and Ministry of Electricity (electricity bills). A greater number of case studies would need more such detailed data and more people prepared to trust and cooperate with the researcher by providing them.

## 1.7 Structure Of The Thesis

**Chapter 1** *Introduction:* This is the starting point of the research. This chapter presents the background to, and an overview of the research field, offering a statement of the problem in the case study location (Saudi Arabia) and explaining how developed countries are dealing with this issue. In addition, this chapter presents the main aim, objectives and research questions. Finally, contributions to the body of knowledge are outlined, together with a brief description of the challenges and limitations encountered.

**Chapter 2** *Literature Review*: This chapter presents a review of recent studies and research related to the subject, and discusses recent solutions and contributions of other researchers. This chapter covers important issues and aspects investigated in the research together with a summary of recent findings, and detailing the background to the many different works that contribute to and support research in this field.

**Chapter 3** *Methodology:* This chapter describes the research plan and approach used to achieve the proposed aim and objectives. A number of approaches are presented to provide a clear indication of the chosen methodology. This chapter describes the four main methods that were employed by the researcher in order to arrive at certain results and/or objectives. Furthermore, the chapter justifies the research design in general and each method in particular, and explains the background to the thesis' research paradigm and philosophy.

**Chapter 4** A *diagnostic study of the factors that influence energy consumption in domestic buildings in Saudi Arabia: public survey analysis and perception:* This chapter describes the first method used in the research. The main purpose of this stage is to determine the current situation and problems with building style, size, and the everyday operation of housing as well as to identify public perceptions of low energy buildings, the willingness of the public to retrofit their homes in order to reduce energy consumption, and the cultural barriers faced. Moreover, this chapter identifies and analyses the factors that result in high energy consumption in the residential sector in

Saudi Arabia, observing that some relate to the culture, religious tradition, and architectural style.

**Chapter 5** *Site visit to case studies; investigations, analysis and solutions for existing homes:* This is the second stage in the research, which aims to determine and identify design weaknesses (form and fabric design) resulting in high energy consumption in domestic buildings in Saudi Arabia. Some data and analyses could not be identified via a public survey, but required site visits and individual analysis and investigation. Site visits to, and analysis of a number of existing homes in different locations across Saudi Arabia are reported in this chapter, in order to address issues such as how the buildings are being designed, and which construction materials are being used in each case. Simulation software tools were employed to investigate energy consumption patterns and identify those design weaknesses that caused high energy consumption. Finally, possible solutions and strategies to conserve energy in existing homes in Saudi Arabia were suggested and validated.

**Chapter 6** *Low Carbon Domestic Design Framework for Sustainable Homes: Delphi Technique Consultation:* This chapter proposes a low carbon domestic design framework for sustainable home models, which designers, architects, developers, building professionals and civil engineers could use to design low energy buildings in Saudi Arabia. Furthermore, the chapter explains how this framework was designed, developed and finalised on the basis of the Delphi technique that is, this chapter discusses the process by which a panel of experts was assembled as well as the three rounds of consultations they underwent in order to arrive at a consensus about the components of the framework

**Chapter 7** *Establishing Standard Domestic Low Energy Consumption Levels for Saudi Arabia and the Wider Middle Eastern Region:* This chapter proposes designs for three low energy houses appropriate for the Saudi climate, context and culture. These three houses are designed on the basis of the framework outlined in chapter 6. This chapter also discusses how the proposed designs respond to the Saudi public needs and satisfy their cultural requirements while keeping energy consumption to a minimum. Furthermore, this chapter presents an in depth analysis of the level of energy consumption achieved in the proposed houses, by benchmarking them against some international low energy house definition standard. Finally, the chapter discusses and establishes an energy consumption definition standard band for Saudi Arabia, including the predicted economic benefit which could be achieved.

**Chapter 8** *Research Conclusion:* This chapter summaries the research findings and presents how the established research questions have been answered through the research stages. Meeting the main aims of the research is presented in this chapter as well as the limitations. Moreover, this chapter describes the future work to be carried out by the researcher and gives recommendations for future researchers, decision makers, architects, developers and homeowners.

# Chapter 2 : Literature Review

## 2.1 Introduction

Reportedly, about 40% of energy use across the world is expended in building construction and maintenance (Zhou et al., 2014, GhaffarianHoseini et al., 2013). More specifically, the building sector consumes 40% of the world's energy, 16% of the world's fresh water, 25% of the timber taken from forests (C. Ghiaus, 2004) and produces 33% of global $CO_2$ emissions (greenhouse gas) (Berardi et al., 2014). In response to these statistics, there has been considerable interest in the developed world, regarding the production of sustainable buildings to promote environmental protection. There is a rising awareness of the need to conserve energy by observing environmentally conscious practices and to produce climate-responsive designs that can deliver building comfort through the utilisation of natural energy resources and systems. Such designs would ideally account for interactions among the dynamic conditions affecting each building's unique environment (Hyde, 2000). In response to the need for reducing energy consumption in the building sector, then, there have been several, proposed and implemented sustainable approaches and energy efficient technologies (Berardi et al., 2014).

Low energy building design is an objective pursued in many countries worldwide. It is extremely important to review the area in order to identify data that have not been adequately covered, and therefore represent a gap in the body of knowledge in this field. To this end, this chapter presents and discusses recent literature detailing studies, theories, techniques and strategies associated with energy consumption and conservation in buildings in hot climates.

Firstly, this chapter will consider the strategies and techniques related to the architectural design of domestic buildings (form) for hot climates. More specifically, this section will refer to such aspects of residential architecture as geometry, typology, proportions and shading techniques, always in relation to energy performance. Secondly, this chapter reviews recent studies associated with efficient design, as related to the housing envelope design, i.e. the fabric of the building, especially in hot climates. The purpose, here, is to identify the best solution for the hot Saudi Arabian climate and context. Finally, this chapter reviews recent investigations and studies relating to renewable energy and generation, especially in hot climates and Middle Eastern regions.

This chapter is structured around the main aim of the study. That is, recently developed sustainability techniques and strategies will be so selected and presented as to provide a comprehensive background for the energy conservation. Accordingly, the information of the following section is divided into four parts (Figure 2.1): (i) sustainable and low energy buildings; (ii) sustainable architectural design in hot climates (form of the building); (iii) housing envelope design in hot climates (fabric of buildings); and (iv) renewable energy and generation.

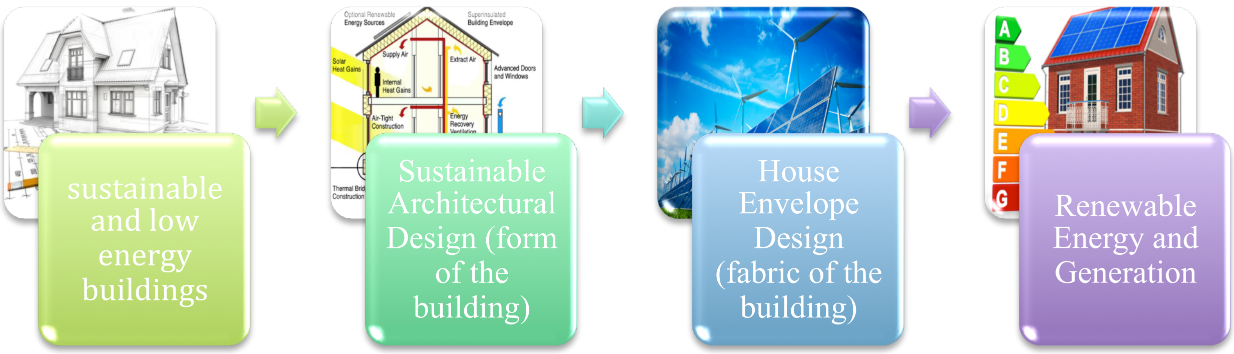



**Figure 2.1 Literature Review Structure**

## 2.2 Sustainable and low Energy Buildings: Policy and Overview

Passive design refers to a series of strategies for architectural design, applied by architects when designing buildings, to respond adequately to climate conditions and requirements (Kroner, 1997). In recent years, there has been increasing interest among entrepreneurs and architects seeking to introduce intelligent buildings into the built environment. They are aiming to achieve efficient levels of energy consumption in buildings, to meet national goals and energy codes regarding the reduction of dangerous emissions and the improvement of corporate image (Ochoa and Capeluto, 2008).

Ochoa and Capeluto (2008) aimed to determine the impact of incorporating intelligence into buildings in environments characterised as hot climates, while focusing on occupant comfort and energy consumption with emphasis on lighting. They clarify that building performance depends on a passive design strategy such as: façade sensors, orientation and daylighting systems , which includes "smart architectural design decisions" (Ochoa and Capeluto, 2008). Their findings illustrate that intelligence in buildings (intelligent buildings) needs to be integrated into the product design process, to incorporate intelligence in buildings with the benefits of technological innovation (Ochoa and Capeluto, 2008).

According to The Saudi Center for Energy Efficiency in King Abdulaziz City for Science and Technology (KACST) in Saudi Arabia, there is a campaign of public awareness regarding the importance and the application of insulation in house envelope and raising the efficiency of using energy in domestic appliances. Internationally, low energy buildings is an important target to be achieved through the employment of principles of passive designs to conserve energy. An overview of definitions for low energy houses across Europe is given in Table -2.1: Source: SBI (Danish House Institute), European Strategies to move towards very low energy Houses, 2008 (Kirsten Engelund Thomsen, 2008, EU, 2009).

**Table 2.1 An Overview Of Definitions For Low Energy Houses Across Europe**

| Country | Official definition |
|---|---|
| ***Austria*** | ▪ Energy consumption from heating systems in low energy Houses should be below 60-40 $KWh/m^2$ per year.<br>▪ The standard for a passive house is 15 $kWh/m^2$ per useful area (Styria) and per heated area (Tyrol) |
| ***Belgium (Flanders)*** | ▪ Class 1 for low Energy houses is 40% lower than for standard houses<br>▪ Class 2 for very low Energy houses means a 60% reduction in energy |
| ***Czech Republic*** | ▪ The energy consumption of a low energy house is: 51 – 97 $kWh/m^2$ p.a.<br>▪ The energy consumption of a very low energy house is below 51 $kWh/m^2$ p.a.<br>▪ The standard of a passive house is 15 $kWh/m^2$ per year |
| ***Denmark*** | ▪ Class 1 for a Low Energy house calculates energy an performance at 50% lower than the minimum requirement for new Houses<br>▪ Class 2 for a low Energy house calculates the energy performance at 25% lower than the minimum requirement for new Houses. |
| ***Finland*** | ▪ The standard of low energy houses is 40% better than that of standard Houses |
| ***France*** | ▪ New houses - the average annual energy consumption for domestic applications such as heating/cooling systems, ventilation, hot water and lighting must be lower than 50 $kWh/m^2$. (from 40 to 65 $kWh/m^2$) based on the climatic conditions<br>▪ Other houses - the average annual energy consumption for heating/cooling systems, ventilation, hot water and lighting must be 50% lower than current House Regulation requirements for new Houses<br>▪ For renovations: 80 $kWh/m^2$ as of 2009 |
| ***Germany*** | ▪ The requirements for consumption of low Energy Houses in the residential sector are 60kWh/($m^2$•a) or (40 kWh/($m^2$•a)<br>▪ Passive Housing - the annual heating demand is lower than 15 $kWh/m^2$ and total energy consumption is lower than 120 $kWh/m^2$ |
| ***England & Wales*** | ▪ 2010 level 3 (25% better than current regulations)<br>▪ 2013 level 4 (44% better than current regulations and almost similar to Passive House)<br>▪ 2016 level 5 (zero carbon for heating and lighting)<br>▪ 2016 level 6 (zero carbon for all uses and appliances) |

In this context, it is difficult to define exactly what can be termed a low energy house given the variety of regulations and climates across Europe and beyond (including US) (EU, 2009). Moreover, what is considered a low energy development in one country may not meet local definitions in another (EU, 2009). An example of this is the Energy Star label in the US, which is awarded to houses that use 15% less energy than what regulations call for in typical new homes (EU, 2009).

## 2.3 Sustainable Architectural Design in Hot Climates

This section of the literature review seeks to provide an examination of the crucial role played by architectural solutions and style in reducing energy consumption and $CO_2$ emissions. Low energy buildings can be achieved through the use of renewable natural energy resources (e.g. solar energy and wind energy), as well as by reducing the energy demand of buildings. Sustainable architecture is the result of an environmentally conscious attitude towards designing, implementing and maintaining buildings and is based on local requirements and needs, construction materials for buildings and reflection on local traditions (Niroumand et al., 2013). Williamson et al. (2003) state that these approaches to sustainable architecture are concerned with two main issues: firstly, they, "*embody the notion that the design of buildings should fundamentally take account of their relationship with and the impact on the natural environment"*; and secondly they are *"concerned with the concept of reducing reliance on fossil fuels to operate a building"* (Williamson et al., 2003). The reduction of energy and natural resource consumption depend on such architectural principles as building shape, shading device strategies and external landscaping, natural ventilation, lighting in buildings and ground heat exchangers (Figure 2.2).

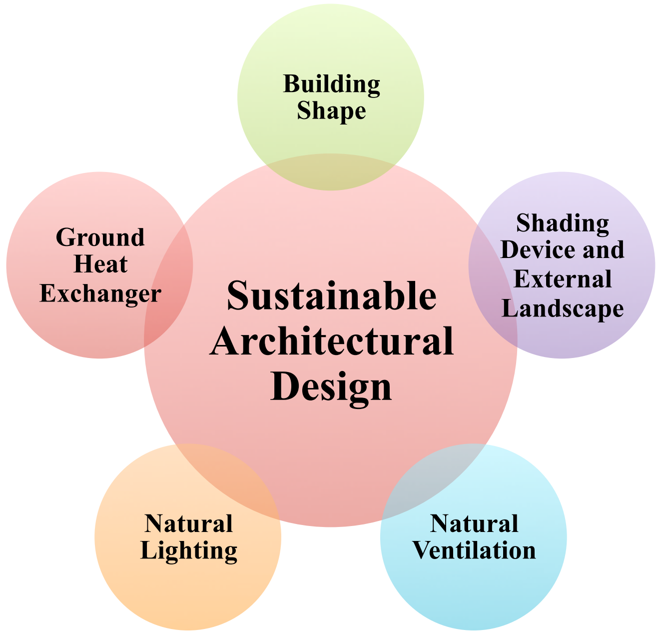



**Figure 2.2 Architectural Design Solutions Structure**

### 2.3.1 Building Shape

Many researchers have confirmed that the shape of the building constitutes a major factor determining its energy consumption (Ourghi et al., 2007, AlAnzi et al., 2009). Hence, optimal building shape design is an important aspect to consider at the design stage, in conjunction with an assessment of local climatic conditions. The shape of a building can reduce solar radiation exposure and transmission load (Feist, 2009). The building shape affects the solar energy received, and consequently the total energy consumed (Mingfang, 2002). Solar heat (i.e. radiation) can increase the energy demand placed upon a cooling system when aiming to achieve a satisfactory level of thermal comfort in the indoor environment.

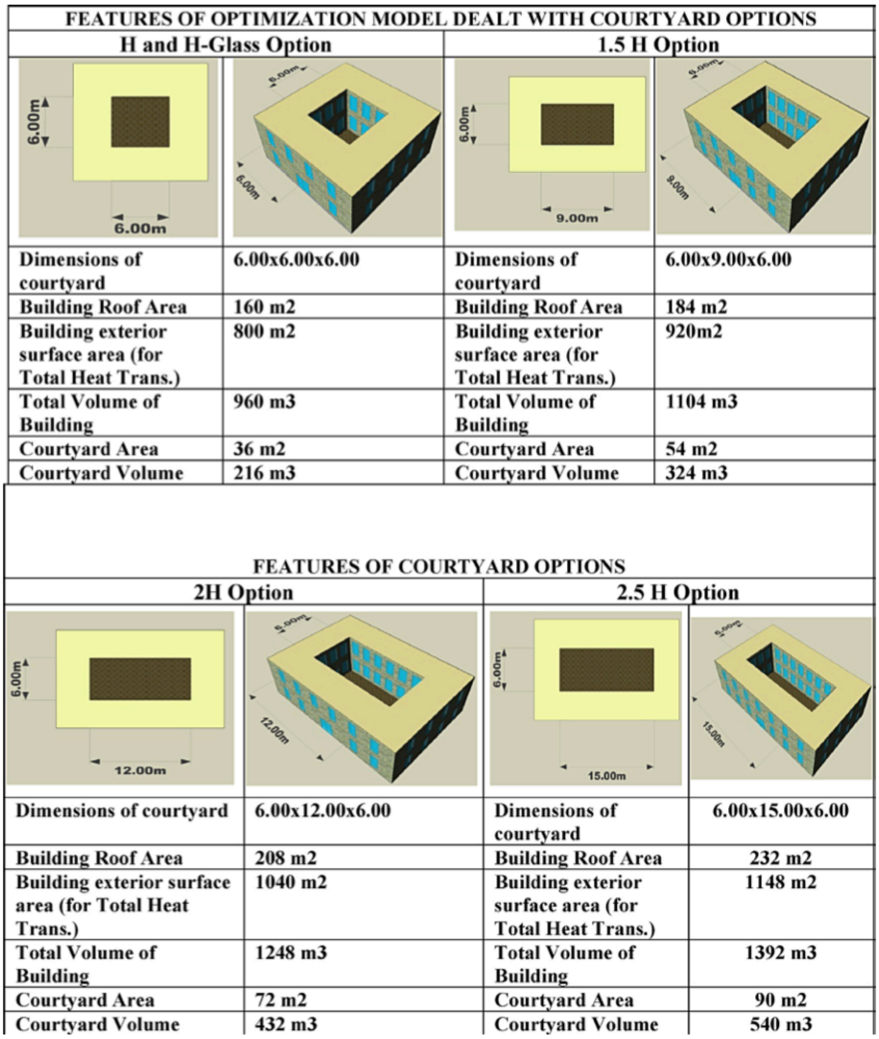
An exterior surface exposed to the sun results not only in heat gain but also in energy loss since it places greater demands on cooling systems. The shape of a building determines the total area of such exposed surfaces and as a result affects the thermal performance of the whole(Pacheco et al., 2012). Bektas and Aksoy (2011) furthermore, note that, when designing a building, it is important to recognise design variables, especially those directly related to the processes of heat transfer. In addition to building shape, they identify both physical environmental and design parameters that influence energy demand. Their findings are summarised in Table 2.2 (Bektas Ekici and Aksoy, 2011).

**Table 2.2 Building Energy Requirements (Bektas Ekici and Aksoy, 2011)**

| Physical–environmental parameters | Design parameters |
|---|---|
| Daily outside temperature (°C) | Shape factor |
| Solar radiation (W/m$^2$) | Transparent surface |
| Wind direction and speed (m/s) | Orientation |
| | Thermal–physical properties of building materials |
| | Distance between buildings |

The above table clearly indicates the multiplicity and complexity of design variables that affect energy performance. Other research, however, notes that the coefficient of building shape in terms of energy demand also depends on the heat transfer through the building envelope (Oral and Yilmaz, 2003, Oral and Yilmaz, 2002). Still, other more recent publications argue that the building shape factor depends on the solar heat factor as well as the ratio of external glazing (Ourghi et al., 2007, AlAnzi et al., 2009).

Another issue that has been investigated in relation to building shape is the presence of a courtyard. Various studies have in fact confirmed the efficiency of its use. For instance, Ratti and et al. (2003) investigated the impact of the shape of a building in environmental terms by including a courtyard in different climate conditions (Ratti et al., 2003).  Another study, conducted by Yaşa and Ok (2014), focuses on energy efficiency of building around a courtyard in hot arid climate regions, and evaluates the comfort status of courtyards (Figure 2.3) (Yaşa and Ok, 2014).



| FEATURES OF OPTIMIZATION MODEL DEALT WITH COURTYARD OPTIONS | | | |
|---|---|---|---|
| H and H-Glass Option | | 1.5 H Option | |
| Dimensions of courtyard | 6.00x6.00x6.00 | Dimensions of courtyard | 6.00x9.00x6.00 |
| Building Roof Area | 160 m2 | Building Roof Area | 184 m2 |
| Building exterior surface area (for Total Heat Trans.) | 800 m2 | Building exterior surface area (for Total Heat Trans.) | 920m2 |
| Total Volume of Building | 960 m3 | Total Volume of Building | 1104 m3 |
| Courtyard Area | 36 m2 | Courtyard Area | 54 m2 |
| Courtyard Volume | 216 m3 | Courtyard Volume | 324 m3 |

| FEATURES OF COURTYARD OPTIONS | | | |
|---|---|---|---|
| 2H Option | | 2.5 H Option | |
| Dimensions of courtyard | 6.00x12.00x6.00 | Dimensions of courtyard | 6.00x15.00x6.00 |
| Building Roof Area | 208 m2 | Building Roof Area | 232 m2 |
| Building exterior surface area (for Total Heat Trans.) | 1040 m2 | Building exterior surface area (for Total Heat Trans.) | 1148 m2 |
| Total Volume of Building | 1248 m3 | Total Volume of Building | 1392 m3 |
| Courtyard Area | 72 m2 | Courtyard Area | 90 m2 |
| Courtyard Volume | 432 m3 | Courtyard Volume | 540 m3 |

**Figure 2.3 Buildings Shaped Around A Courtyard In Hot Arid Climate Regions** (Yaşa and Ok, 2014)

The researchers observe that the shaded area of a courtyard reduces as the sun Rises, in the summer periods. The impact from the shading of a courtyard, therefore, is the smallest in the summer, when the highest demand is placed on cooling systems due to high temperatures. In the end, the researchers conclude that, the impact of a shadow, due to a courtyard, for reducing cooling energy in the summer, is less than the impact of shadowing on heating energy need during the winter (Yaşa and Ok, 2014). This finding is particularly significant for hot arid or hot humid regions because it indicates that the benefits of incorporating courtyards in such regions is minimal.

However, it was found that creating a roof with an optimal shape could play a role in energy conservation and generation. An investigation conducted by Islam Abohela et al. (2013) aimed to discover the impact of the shape of the roof (using different roof shapes - Table 2.3) on energy return from optimally positioned roof mounted wind turbines. They aim to point within different urban configurations. They suggested an increase in energy yield (generation) can be achieved, reaching up to 56.1% more energy generation in the form of electricity, through the addition of a vaulted roof to a building (Abohela et al., 2013).

**Table 2.3 The Impact Of The Shape Of The Roof (Abohela et al., 2013)**

| | 0° | 45° | 90° | 135° | 180° |
|---|---|---|---|---|---|
| Flat Roof | | | 0° | 45° | 0° |
| Location of maximum recorded *U* value above 1.3*H* | C2-3 | C2-2 | C2-3 | C2-2 | C2-3 |
| Vertical location | 1.45*H* | 1.3*H* | 1.45*H* | 1.3*H* | 1.45*H* |
| Maximum recorded *U* value above 1.3*H* | 1.095*U* | 1.12*U* | 1.095*U* | 1.12*U* | 1.095*U* |
| Percentage of increase in power | 31.3% | 40.5% | 31.3% | 40.5% | 31.3% |
| Domed Roof | | | 0° | 45° | 0° |
| Location of maximum recorded *U* value above 1.3*H* | D3-3 | D3-3 | D3-3 | D3-3 | D3-3 |
| Vertical location | 1.3*H* | 1.3*H* | 1.3*H* | 1.3*H* | 1.3*H* |
| Maximum recorded *U* value above 1.3*H* | 1.12*U* | 1.14*U* | 1.12*U* | 1.14*U* | 1.12*U* |
| Percentage of increase in power | 40.5% | 48.2% | 40.5% | 48.2% | 40.5% |
| Gabled Roof | | | | 45° | 0° |
| Location of maximum recorded *U* value above 1.3*H* | G5-1 | G3-5 | G2-3 | G3-5 | G5-1 |
| Vertical location | 1.6*H* | 1.4*H* | 1.3*H* | 1.4*H* | 1.6*H* |
| Maximum recorded *U* value above 1.3*H* | 1.05*U* | 1.09*U* | 1.075*U* | 1.09*U* | 1.05*U* |
| Percentage of increase in power | 15.8% | 29.5% | 24.2% | 29.5% | 15.8% |
| Pyramidal Roof | | | 0° | 45° | 0° |
| Location of maximum recorded *U* value above 1.3*H* | P4-2 | P4-4 | P4-2 | P4-4 | P4-2 |
| Vertical location | 1.3*H* | 1.3*H* | 1.3*H* | 1.3*H* | 1.3*H* |
| Maximum recorded *U* value above 1.3*H* | 1.05*U* | 1.08*U* | 1.05*U* | 1.08*U* | 1.05*U* |
| Percentage of increase in power | 15.8% | 26% | 15.8% | 26% | 15.8% |
| Vaulted Roof | | | | 45° | 0° |
| Location of maximum recorded *U* value above 1.3*H* | V3-3 | V3-3 | V2-2 | V3-3 | V3-3 |
| Vertical location | 1.3*H* | 1.3*H* | 1.35*H* | 1.3*H* | 1.3*H* |
| Maximum recorded *U* value above 1.3*H* | 1.16*U* | 1.14*U* | 1.083*U* | 1.14*U* | 1.16*U* |
| Percentage of increase in power | 56.1% | 48.2% | 27% | 48.2% | 56.1% |
| Wedged Roof | | | | | |
| Location of maximum recorded *U* value above 1.3*H* | W5-1 | W5-5 | W2-4 | W3-2 | W2-1 |
| Vertical location | 1.45*H* | 1.3*H* | 1.3*H* | 1.3*H* | 1.4*H* |
| Maximum recorded *U* value above 1.3*H* | 1.03*U* | 1.07*U* | 1.075*U* | 1.14*U* | 1.08*H* |
| Percentage of increase in power | 9.3% | 22.5% | 24.2% | 48.2% | 26% |

Finally, Zaki et al. (2012) advocate the use of passive architectural design principles in terraced houses, with a view to promote natural thermal comfort for residents. They have adapted the design strategy of passive architecture (re-orientating its floor plan, attribution of landscape area and size of land) to terraced houses that alleviate the demand for mechanical cooling (Figure 2.4). They found that a major energy reduction (approximately 83%) can be achieved by using passive architecture design principles (Zaki et al., 2012).

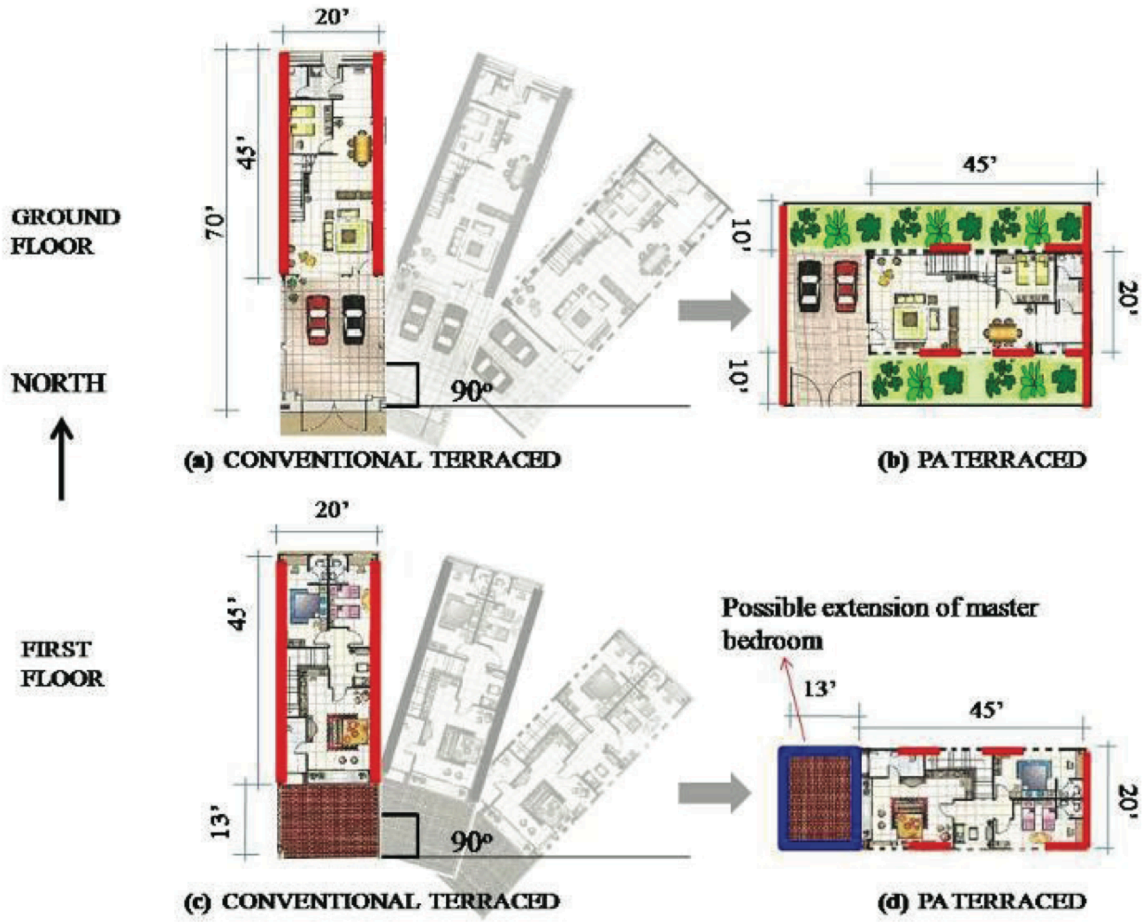



**Figure 2.4 Conventional Terraced House Transformed To Be A Passive Architectural Terraced House (Zaki et al., 2012).**

### 2.3.2 Shading Devices and External Landscape

In countries with hot climates, cooling the space around a building can play a role in reducing the need to expend energy for air conditioning. Many researchers, who have examined possibilities for energy conservation in hot climatic conditions, have examined this factor. First, it is well known that adding trees to the external landscape can offer shading that lowers the levels of cooling energy required (Nikoofard et al., 2011, Akbari et al., 1997, Pandit and Laband, 2010). According to Akbari H (2002), urban shade and trees can deliver important benefits in terms of reducing the energy demand for cooling energy in a building, and improve external air quality by minimising smog (Akbari, 2002).

Another study carried out by Simpson and McPherson (1998), evaluated and simulated the influence of tree shading on housing energy use in 254 properties in California. They found that planting an average of three trees per property could have a significant effect; reducing annual and peak cooling energy use by 7.1% and 2.3%, respectively (Simpson and McPherson, 1998). This study illustrates how applying an optimal design to the external landscape can influence air conditioning energy consumption in countries with hot climates like Saudi Arabia, and that this factor must be considered when designing low energy housing in such countries. In addition, the effect of broad leaves has been considered in reference to prospective energy savings. The shading effect from broad leaved evergreen and deciduous trees was evaluated by Higuchi and Udagawa (2007). They report that by planting such trees to shade buildings, savings of up to 20% on annual cooling energy could be made (Higuchi and Udagawa, 2007).

Non-use of a shading system in a building can impact energy demand and cause increased energy consumption for air conditioning. A study conducted by Farrar-Nagy et al. (2000), has evaluated opportunities for the reduction of cooling energy in a hot dry climate through the use of architectural shading, windows and site shading by means of efficient landscaping. Their findings are that the absence of shading in a building could increase annual cooling energy requirements by as much as 24%, although the precise percentage depends on the orientation of the building, the types of the windows, and existence of any overhangs (Farrar-Nagy et al., 2000). Solar heat gains reduction in a building can be achieved with fixed shading and movable shading (e.g. Persian shutters or Venetian blinds) of windows. This method is a distributed and efficient measure, with the reduction of solar loads in summer potentially being contingent on the size of the window and its orientation (Feist, 2009).

Overhangs belong to a broader category of man-made shading devices that can be classified as interior and exterior devices. Kischkoweit and Lopin (2002) studied different passive-solar shading systems and their effects on interior day-lighting conditions. They note that sunshades are not only responsible for preventing overheating but are also potentially responsible for minimising use of natural light for visual tasks indoors (Kischkoweit-Lopin, 2002). In later research, Li and Wong (2007) have evaluated the performance of day-lighting, as well as energy use, in a commercial building shaded by nearby buildings in Hong Kong. Their research established a number of related equations that can assist in the prediction of potential energy reductions through shading due to external obstructions (Li and Wong, 2007).

A common practice, however, is to place vertical and horizontal man-made devices that provide shading in response to the position of the sun and a particular architectural design.The research seeking to identify the particular characteristics (i.e position, sizes, materials etc.) of such devices is immense. A practical tool has been designed, for example, by Jorge et al. (1993) to determine the optimal size of shading devices, whether horizontal or vertical (Jorge et al., 1993). The researchers have presented a nomogram for use in regions with a Mediterranean climate; the aim being to optimise the design of shading devices. This nomogram can be used to evaluate the performance of a proposed external fixed shading device; although a graphical approach leads to an error of about 10%, which is quite significant (Jorge et al., 1993). Another study has examined the design of external louvers for buildings, and investigated the influence of louver shading devices on the different façades of a building (Palmero-Marrero and Oliveira, 2010). The study concludes that an external louver, positioned as a shading device strategy in a building, will contribute to improving indoor comfort levels, as well as leading to energy conservation (Palmero-Marrero and Oliveira, 2010).

### 2.3.3 Natural Ventilation

Natural ventilation has been used for centuries, and remains one of the most important strategies in sustainable building design. It is recommended that a spread-out design for buildings with high ventilation rates can be used in hot humid climates where air-conditioning is not an option (such as for cost reasons) (Feist, 2009). Many studies have been conducted to address the benefits of natural ventilation, as well as possible implementation techniques that take into account both natural air flows and mechanical options. It is the latter form of ventilation, though, that has attracted growing interest due to its potential advantages (Khanal and Lei, 2011). More specifically an extensive number of studies have focused on solar chimneys and the associated concept of absorptivity by Lee and Strand (2009), for example report that improvements to airflow rates can reach 57% by increasing the solar absorptance of the absorber wall of a solar chimney from 0.25 to 1.0 (Lee and Strand, 2009). The temperature of the surface of the absorber wall can be increased significantly by increasing solar absorptance. They therefore suggest the highest absorptance possible for the absorber wall should be used, to maximise the levels of ventilation in the building (Lee and Strand, 2009). A solar chimney can promote natural ventilation using a top sloping roof to harvest solar heat and transfer this heat into the air via a sloped channel inducing a flow of air (upward) (DeBlois et al., 2013).

Dai et al (2003) have conducted an analytical study to improve natural ventilation in a solar house. They used both a solid adsorption cooling cavity and a solar chimney. They found that on a typical day the solar house, comprising of a 2.5 $m^2$ solar chimney, can create an airflow rate of over 150 kg/h (Dai et al., 2003). The rate of ventilation at night was also found to increase by up to 20% when using the solar adsorption cooling cavity (Dai et al., 2003). In hot and humid climates, Wong et al. (2008) have argued that the performance of a double-skin façade "*depends closely on the chosen ventilation means within its intermediate space*" and that, therefore, natural ventilation is an energy saving measure capable of further improving the effects of various sustainability measures (Wong et al., 2008). In new construction projects, the concepts of passive cooling and heating were employed to enhance environmental awareness (DeBlois et al., 2013). In domestic settings, using a sloped roof or a solar chimney was the subject of earlier studies (Aboulnaga, 1998).

As was mentioned previously, cooling a house can be achieved with natural ventilation. However, in some cases, a cooling system that relies on energy use is necessary. Energy can be used for either a mechanical cooling system or a passive cooling system (Feist, 2009). Raman et al. (2001) tested passive solar systems that provide cooling, heating and ventilation in hot arid climates and in cold climates. They state that a passive system effectively moderates the temperature variation in a room (Raman et al., 2001). A system comprising of a collector positioned on a south wall, and a roof duct involving an evaporative cooling surface, was found to maintain an indoor temperature of approximately 30°C when the ambient temperature reached as high as 42°C during the summer period (Raman et al., 2001). According to Verma et al. (1986), the performance of a passive cooling system, using an evaporative cooling technique on the roof, was found to be effective, significantly reducing the air temperature in a room (Verma et al., 1986).

An alternative option is offered by Maerefat and Haghighi (2010), who propose enhancement of passive cooling and natural ventilation in a solar house, based upon low-energy-consumption techniques by employing both a solar chimney and an evaporative cooling cavity. They reported that in the event of decreasing relative humidity to below 50%, the system was effective for air-conditioning in hot conditions (i.e. 40°C), delivering a better performance with a concurrent configuration (Maerefat and Haghighi, 2010).

Diverse methods are available to ensure that the indoor temperature remains low in the summer without active cooling. Some methods are simple, well-known and widely distributed, whereas others are exotic. Whilst some of the methods employed are passive, they may still require auxiliary energy for pumps, fans, etc. These methods are called hybrid cooling strategies and require much less energy than standard air-conditioning units.

Reducing the infiltration and transmission of heat gains from hot ambient air is useful in countries with very hot climates. This can be achieved by using ventilation, air tightness heat recovery, and insulation (Feist, 2009). On the other hand, excess heat can be removed with natural ventilation, especially at night. In windy conditions, natural ventilation and ensuring the use of stack effect factors can create high airflow rates (Feist, 2009). Opening windows at different levels, while insuring a connection inside the building (such as an open staircase) is understood to be a simple application of the stack effect (Feist, 2009).

Mechanical ventilation can be applied to an entire building to reduce heat flows. This can be achieved by using a simple system, such as an attic fan, which removes solar heat from the attic (Feist, 2009). The air velocity surrounding people can be increased by ceiling fans, but this is not classified as passive cooling. Ceiling fans can also reduce thermal discomfort in warm conditions (Feist, 2009). Heat recovery and adiabatic cooling are used in ventilation systems. In such systems, exhaust air is humidified and cooled, then transferred over the heat exchanger to cool the air supply (Feist, 2009).

On the other hand, subsoil heat exchangers cool down transferred external air (Feist, 2009). Soil cooling is a method which uses the evaporation enthalpy of water. This approach can be applied in a building to cool shaded ground located around, under or on top of a building (Feist, 2009). Different types of ground coupling can also make use of relatively constant ground temperatures (Feist, 2009).

### 2.3.4 Lighting

Natural lighting is an important factor to consider when designing homes, due to the health advantages of daylight and its role in energy conservation. Recently, there has been an increased interest in integrating natural lighting (day- light) with electric-lighting to reduce the energy consumption in buildings (Li and Lam, 2001). Many studies have reported the benefits of natural lighting, e.g. daylight promotes householder health benefits and plays a significant biological role in controlling the physiological and psychological rhythms of human beings (Choi et al., 2012). Gains reductions can occur by using efficient lighting and appliances, as well as DHW systems that reduce heat losses. This saves energy in both the production of excess heat and in its removal (Feist, 2009).

According to Feist (2009), the sun can be both a friend and an enemy to buildings. There is a need for caution, since buildings with poor climatic design can overheat in hot and even in cold climates. The use and manipulation of the energy advantages of the sun have an important role in sustainable design: solar energy must be exploited in passive solar designs as a pollution free alternative to burning fossil fuels (Feist, 2009).

On the other hand, access to daylight and sunlight affects the form of buildings and cities, and the provision of electric lighting is one of the biggest end uses of electricity in the world. Occupant perception regarding daylight in a building is a key factor when controlling the use of electric lighting (Richardson et al., 2009). Mahapatra et al. (2009) have studied the performance of electrical lighting and proposed solutions that promote better levels of light, keep energy consumption to a minimum, and as a result lower rates of $CO_2$ emissions. They assert that natural energy resources can be used instead of electricity, particularly in areas where there is no grid electricity (Mahapatra et al., 2009). According to Mahapatra et al. (2009), there are architectural considerations of solar photovoltaics in each individual house, demanding intelligent use of modern systems of bio-energy. These are a better choice for the provision of a good quality of lighting in rural areas (Mahapatra et al., 2009).

### 2.3.5 Ground Heat Exchangers

To improve ventilation through a natural cooling system, the use of an earth to air heat exchanger (EAHE) is considered a viable architectural solution. This technique can also contribute to a reduction in a building's indoor temperature (Hollmuller and Lachal, 2001). As the ground exhibits high thermal inertia, the temperature at a certain depth remains stable throughout the year, which is potentially helpful in summer as a heat sink and in winter as a heat source (Hollmuller and Lachal, 2001). The former option is applicable in hot climates for cooling purposes. Application of the EAHE technique requires an in depth understanding of the heat and humid dynamics at work in an earth to air heat exchanger (Kumar et al., 2006). Different analytical and numerical models have attempted to examine thermal behaviour and cooling, and the preheating potential of EAHE (Kumar et al., 2006).

Maerefat and Haghighi (2010) have investigated the techniques for passive cooling, by using an EAHE in conjunction with a solar chimney (illustrated by Figure 2.5). They conclude that the performance of this system depends on the exterior temperature of the air, solar heat (radiation) and the configuration of both an earth to air heat exchanger and a solar chimney. They also claim that when cooling demand and external temperatures are high, suitable configurations can provide good internal conditions (Maerefat and Haghighi, 2010).

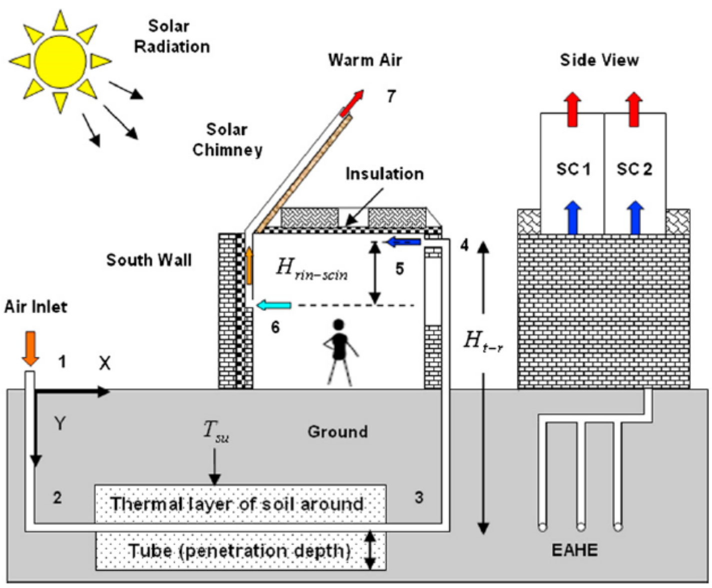



**Figure 2.5 External Air Temperature, Solar Radiation And The Configuration Of Both An Earth To Air Heat Exchanger And A Solar Chimney (Maerefat and Haghighi, 2010)**

Another study has developed a theoretical model of heat exchange through the earth, for hot and arid climatic conditions, to calculate the cooling potential of these devices, as well as the outlet air temperature. They found that an EAHE can reduce the demand for cooling energy in a typical house by approximately 30% (Al-Ajmi et al., 2006).

## 2.4 House Envelope Design in Hot Climates

South European countries have conducted numerous studies into how to achieve a reduction in the energy consumed for cooling systems in buildings, while maintaining a satisfactory level of internal thermal comfort in hot periods (summer season) (Rossi and Rocco, 2014). Many of these studies elaborated on the importance of selecting a building fabric with high thermal inertia in order to save energy while insuring indoor comfort during the summer (Aste et al., 2009). Arguably one of the most important elements of a sustainable building is its building fabric. The benefits of an appropriately designed building fabric are energy reduction and a comfortable indoor temperature over a long period of time. The basic components of the building fabric are external walls, windows, doors, roofs and flooring.

Operational energy is the energy needed to operate cooling and heating systems, light the building, insure adequate ventilation, and perform domestic activities. Hence, energy consumption to operate cooling and heating systems has a bulk use that depends on the heat gain or loss of the building (Ramesh et al., 2012).

A high level of heat gain or loss increases the need to operate cooling or heating systems respectively and therefore, causes greater energy consumption in a building. A building envelope or building fabric designed with low thermal conductivity and suitable heat capacity can play a significant role in reducing the heat gained or lost through a building as well as its energy needs (Ramesh et al., 2012). Reducing solar heat gains through a building's construction materials can be achieved with thermal insulation, cavities, radiation barriers, and reflective colours (Feist, 2009).

In this section each type of building fabric (house envelope) will be discussed separately, and emphasis will be placed on fabric design for hot climates. Hence, this section will be separated into four main areas of discussion: (a) Insulation in housing envelope and thermal comfort, (b) external walls design and components, (c) roof / floor design and principles, and (d) windows and glazing design (Figure 2.6). An evaluation will also be provided of the results of previous studies for each type of the building fabric, with particular attention being paid to the best housing envelope design for a hot climate.

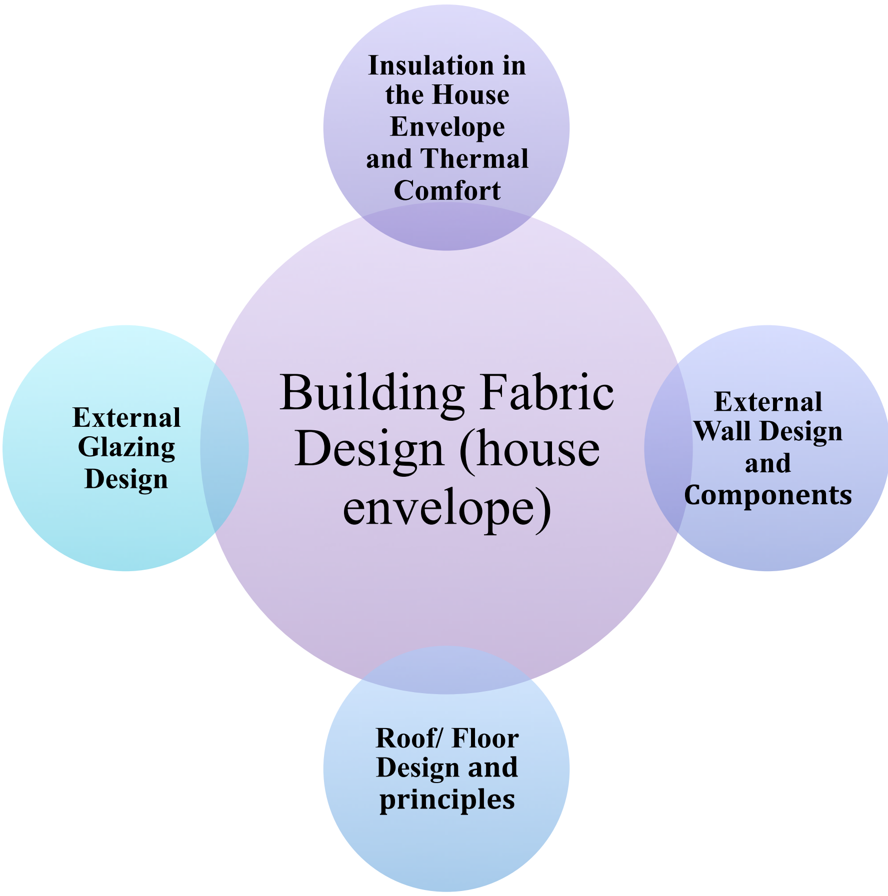



**Figure 2.6 House Envelope Design Section Structure**

### 2.4.1 Insulation Within the House Envelope and Thermal Comfort

Efficient thermal insulation in the house envelope (external walls and roof) will not only conserve the energy required to operate the cooling system (air-conditioning), but will also contribute by saving annual energy cost (Al-Homoud, 2004). Moreover, thermal insulation contributes to maintaining the thermal comfort in a building for longer periods of time without the need to use a cooling system, especially during the periods between seasons (Al-Homoud, 2004).

Some studies have reported on the efficiency of the application of higher thermal insulation to building fabric, to reduce energy consumption (Ramesh et al., 2012). According to Aste et al (2010), the energy performance of a building will improve when using abundant insulation in the building envelope, and considerable thermal mass (Aste et al., 2010). Another study carried out by Citherlet and Defaux (2007) has analysed and compared family homes as case studies and concludes that by altering the thicknesses and type of insulation it is possible to deliver a substantial energy saving of about 50% (Citherlet and Defaux, 2007). An additional study by Mitraratne and Vale (2004), in New Zealand, recommends the application of insulation of significant thickness to timber framed houses as an energy reduction strategy. It becomes apparent , then, that usage of efficient insulation is imperative for the production of energy efficient houses (Mithraratne and Vale, 2004).

Selecting cool materials when designing a house envelope is one way of minimising subsequent energy consumption by a cooling system. A study was conducted by Revel et al (2014), which evaluated the potential for such a system to offer a cost-effective solution to reduce energy consumption by cooling system in regions characterised by hot summers and mild winters, such as Mediterranean countries (Revel et al., 2014a). They proposed an experimental and numerical method to evaluate the thermal performances of different construction materials developed by the author in a former study (Revel et al., 2014b). These materials are: (a) cool coloured ceramic tiles, (b) acrylic paints for facades, and (c) bituminous membranes for the building envelope on real buildings (Revel et al., 2014a). They pointed out that, in the case of cool materials, up to 50% of heat flux reduction occurs through the building envelope with wall temperatures reaching up to 4.7 °C. Moreover, annual cooling energy savings (from 0.6-3.5 $kWh/m^2$) have been measured at different localities in Europe. The researchers reported that, in hot climates, cool façades can have a positive influence on annual energy reduction figures (Revel et al., 2014a).

Kuzman et al. (2013) compared different construction materials, including different types of construction for passive houses (e.g. wood farm, solid wood, aerated concrete, and brick) (Kuzman et al., 2013). They also looked at the advantages and disadvantages of the most common construction materials used. Their methodology employed

Analytic Hierarchy Process (AHP). They found that wood construction could promote energy efficiency in domestic buildings (Kuzman et al., 2013).

According to Zainazlan Md Zain et al. (2007), varying thermal comfort requirements among people living in different climates demand that architectural design concepts for a building must take into account local preferences. Different researchers have examined thermal comfort from various perspectives, with a common goal to establish how best to satisfy people's needs (Zain et al., 2007).

Zainazlan Md Zain et al. (2007) have described typical strategies to improve comfort in hot, humid climates (Malaysia) in the absence of air conditioning. They reported that, by knowing how solar radiation behaves, a suitable building envelope can be integrated to manage heat effectively through solar radiation behavior and the characteristics of a building's envelope using a strategy to flush out the extra heat (Zain et al., 2007). The study also stated that though the potential for thermal comfort from passive cooling is limited in rural areas (Zain et al., 2007).

### 2.4.2 Efficient External Walls Design in Buildings

When designing low energy homes, it is extremely important to consider an efficient housing envelope; external walls are one of the main components of the building envelope. Many techniques for the efficient design of external walls have been considered and proposed in recent research. Al-Homoud (2004) evaluated the effectiveness of thermal insulation in different types of buildings in the Kingdom of Saudi Arabia. He stated that energy conservation pertaining to thermal insulation is generally higher in skin load-dominated housing (Al-Homoud, 2004). That means, the higher the internal heat gains of buildings, the lower the energy conservation level reported. This can be improved by the application of thermal insulation into the external walls.

Several investigations have been conducted to determine the most appropriate thermal insulation thicknesses (Li and Chow, 2005, Bojic et al., 2002). For example, Zhu et al. (2009) have stated that thermal mass in an external wall can enable heat to be saved during the daytime and released during the night (Zhu et al., 2009). However, in desert climates, with high 24-h ambient temperature and strong sunlight, more heat will be saved than can be subsequently released, resulting in increased energy demand for cooling (Zhu et al., 2009).

In the context of the Bahrain region, Radhi (2009) reports that thermal insulation in an external wall offers a 25% reduction in energy consumption with regard to skin load-dominated buildings (Radhi, 2009). Additionally, if thermal codes are applied to internal load-dominated buildings, the energy consumption drops to 5%. Radhi (2009) claims that energy consumption in the Middle East can potentially be reduced to approximately 7.1%, and that $CO_2$ emissions can be reduced to approximately 23.4 million metric tonnes.

Another strategy resulting in efficient external walls is the double wall technique. Utama and Gheewala (2009) have assessed life cycle energy (kWh/m² year) in an apartment in Indonesia (city of Jakarta) (Utama and Gheewala, 2009). They used clay bricks as a constant material but varied the configuration of the external walls; that is they first used a double wall and then they used a single one. They found that, a double wall is more efficient in terms of energy performance, by about 40%. Another study was conducted by Utama and Gheewala (2009), who examined cement and clay in single houses in Indonesia. They found that, the energy performance for clay houses was better, than cement house (Utama and Gheewala, 2009).

Other studies have focused on the employment of mud as a construction material and have illustrated its efficiency for energy performance. For example Coffman–et al. (1980)–confirm that mud external walls have a natural cooling effect (Coffman et al., 1980). Similarly, Duffin and Knowles (1981) identify mud construction as a means to control indoor temperatures but they add that suitable proportioning of double or triple layers of different construction materials would further improve both comfort levels and energy efficiency (Duffin and Knowles, 1981). Finally, Chel and Tiwari (2009) report that, in the context of India, the mud house is efficient in terms of energy performance, as well as being an eco-friendly home, that delivers thermal comfort (Chel and Tiwari, 2009).

Considerable research has also been undertaken regarding the thickness and configuration of external walls. Bolatturk (2006) stated that energy savings can be achieved by using a suitable thickness of insulation in buildings. When the thickness of insulation is between 2 and 17 cm, the energy saved can range from 22% to 79% (Bolattürk, 2006). Moreover, the thicknesses of an external wall can play a significant role in energy saving. Fang and Li (2000) suggest that the best structural thickness in passive solar-heated residential buildings is 37cm for brick, 40 to 45cm for high concrete walls, and 35 to 40cm for low concrete walls (Fang and Li, 2000). Clearly the construction of thicker external walls is a costly proposition. However, the long term reduction of operational costs resulting from such construction eventually leads to both economic and environmental benefits(Sisman et al., 2007).

On the other hand, thicknesses of external walls can support passive cooling strategies, including thermal mass (Feist, 2009). This can be achieved by buffering heat during the daytime and releasing it at night. The thickness of external walls, can also buffer solar heat in the daytime, and release it during the night, as seen in the adobe walls in Mexico and the southern US (Feist, 2009).

Cavities within external walls have also been extensively researched, as they play a primary role in heat transmission. A study conducted by Najim (2014) confirms that, improving thermal performance of the external load-bearing wall of a domestic building can be the best option in terms of reducing energy consumption to run a cooling system. Moreover, the study also confirms that, compared with other approaches, the incorporation of air-cavities in external walls will have a greater effect on their performance (Najim). Physically the external envelope will play a significant role in heat transmission. Because external walls are able to store heat, they can contribute to both heating and cooling their corresponding interior spaces. To attain such effects, however, requires appropriate manipulation (Byrne et al., 2013). When cooling is the desired effect, a cavity insulation must be installed so that it confines heat storage in the external leaf of the wall and consequently forces the stored energy to be released to the outside (Byrne et al., 2013). These studies display how far these strategies can be applied in regions with a hot climate, such as Saudi Arabia or the GCC countries, in order to save energy via efficient external wall design. Additional techniques (cavity depth and cellulose insulation) can be applied when designing external walls, to increase the efficiency of the house envelope. In their research Aviram et al. (2001) have focused on cavity depth for external walls. They assessed the performance of varying cavity depths by altering the temperature of the ground surface at the base of the cavity (Aviram et al., 2001). As an alternative, the uses of cellulose insulation has been studied by Nicolajsen (2005). Nicolajsen (2005) investigated the thermal performance of cellulose insulation materials and compared this with the thermal performance of stone wool batts (Nicolajsen, 2005). He found that, the thermal performance of stone wool batts was higher than that for the types of cellulose tested (Nicolajsen, 2005).

Wang et al. (2013) have analysed the efficiency of water thermal storage walls in new and retrofitted buildings. Using variance analysis, they found that there were four major structural parameters influencing energy consumption and thermal comfort: (a) building shape coefficient, (b) orientation of the building, (c) glazing ratio of the southern wall, and (d) the structure of interior partitions (Wang et al., 2013).

### 2.4.3 Efficient Roof Design

The roof of the building is the second part of the housing envelope that determines energy performance. The results of recent studies into roof design and insulation materials will be discussed in this section, which will be divided into three main areas; green roof design, white roofs and reflection, and roof insulation.

One of strategies when designing an external roof with the aim of achieving energy savings is the Green Roof. Green Roofs which are also called roof gardens, eco-roofs, or living roofs include planting on the external surface of the roof (Parizotto and Lamberts, 2011). The external roof of buildings is an envelope component offering significantly advanced solutions in terms of energy conservation for cooling the inside of buildings or improving the internal thermal conditions in non-cooled buildings (Zinzi and Agnoli, 2012). In addition, adding cool materials to the roof of a building will maintain a low temperature, even under hot conditions, such as when facing solar heat (sun). They function by reflecting the sun's heat (solar radiation) and radiating it away during the night.

Examples of vernacular architecture from Northern European countries have been employed in research to demonstrate the benefits of green roofs (Coutts et al., 2013). The materials, including the vegetation, used in green roofs act as thermal insulation and they result in energy efficiency (Zinzi and Agnoli, 2012). Furthermore, they offer increased insulation due to the soil and evapotranspiration, thus keeping the external roof of the building cool under solar radiation (Zinzi and Agnoli, 2012). At the same time, the incorporation of green roofs has additional benefits, such as, improvement in the quality of water runoff (Bates et al., 2013). Many existing studies note that different types of Green Roofs are used in different locations (countries), confirming the advantages of selecting different building features to suit different climates (Williams et al., 2010, Peri et al., 2012).

However, because of the complexity of installing and maintaining a proper green roof, simpler alternatives have been explored. Selecting a light coloured external roof's surface has been proposed, due to the supposed efficiency of lighter colours in reflecting the sun. There are important differences in heat gain between lightly coloured and dark roof surfaces (Suehrcke et al., 2008). A roof which is designed to be highly reflective, such as a white roof surface will be cooler during sunny periods, minimising the demand for energy to cool the building (ANSI/ASHRAE, 2004). Both weathering and ageing, however, play a role in minimising the solar reflection from cool roofing materials (Akbari et al., 2005)

Suehrcke et al. (2008) conducted a study in hot climate conditions, and proposed the classification of roof colours into, dark, medium, light and reflective ones. According to their calculations, a dramatic reduction in downward heat flow could be achieved if a reflective or light coloured roof surface were used. This reduction correlates with a reduction in energy consumed by a cooling system (Suehrcke et al., 2008).

Based on the results of a numerical simulation, Suehrcke et al. (2008) argue that a roof with a light colour delivers approximately 30% reduction of internal air temperature and heat gain when compared with a dark coloured roof (Suehrcke et al., 2008). They add that a quantitative assessment of the effect of roof colour (more correctly, roof solar absorption and thermal emission) is complicated by the following factors (Suehrcke et al., 2008):

1) The benefits of light roofs are not necessarily held to be positive in locations that require both cooling and heating systems. The upward and downward heat flow will require separate treatments.
2) The external surfaces of roofs will absorb some solar heat and therefore heat flows need to be measured to judge the precise effect of roof colour
3) The differences between external and internal temperature are variable, while heat flows are influenced by the thermal mass of an external roof.

4) The solar absorption of an external roof can be affected over time, due to dust and the effects of external damage (ageing).

For hot climate conditions, according to Suehrcke et al. (2008) "*it is widely recognised that a reflective white roof surface instead* of *a dark one can be of great benefit*" (Suehrcke et al., 2008). Roofs that are white in colour can improve occupants' comfort in the home and reduce the load on air conditioning systems.

In regard to the insulation of roofs, a cooling process can be achieved via radiative cooling from the roof of a building with unglazed solar collectors, or one with movable insulation (Feist, 2009). Evidence suggests that the best solution is to utilise three layers of insulation of the same thickness, two of which should be placed on the internal and external sides of the roof, and one in the middle in order to minimise periodic heat flux passaging to the building (Ozel and Pihtili, 2007). It can save a huge amount of energy, if the insulation is positioned suitably, but if the insulation is positioned incorrectly, it may have no effect. The thermal resistance (R-value) of the insulation of a building's roof is increased by up to 1.5 if the thermal value and reflection of the roof have low values (0.65 and 0.75, respectively) (ANSI/ASHRAE, 2004).

Halwatura and Jayasinghe (2008) conducted a study that confirmed that an insulated roof slab can perform better when compared with a lightweight roof in hot and arid conditions (Halwatura and Jayasinghe, 2008). In detail, their study showed that, reflective insulation, including 25mm of insulation and a 38mm of insulation results in efficient performance, where 25mm can offer a noteworthy improvement. However, a 25 mm thickness of insulation offers only minor improvement compared with a 38mm thicknesses of insulation (Halwatura and Jayasinghe, 2008). This evidence affords the designer flexibility when designing the house envelope (external roof).

### 2.4.4 Windows and Glazing Design

This section will investigate the results from recent studies, relating to window design and glazing. It will be divided into three main areas: the importance of windows, window design, and glazing.

It is well known that, external window design (glazing) is one of the most important elements considered by a designer when designing low energy homes for hot climates. It is common practice in modern dwellings to use large windows which result in high rates of heat transfer. Moreover, windows allow daylight into a building providing sufficient lighting during the day and meeting at least some of lighting needs in internal spaces (Askar et al., 2001). A suitable design for windows, offering natural lighting can improve appreciation of the indoor atmosphere (Askar et al., 2001). In the Middle East, buildings are designed to have large areas of glazing. A study was conducted by Askar et al. (2001), and showed that recent building designs in the Middle East involved large areas of glazing (Askar et al., 2001). However, this creates high electricity demand to run a cooling system (air conditioning) (Askar et al., 2001). A suitable design of windows is one way to reduce this demand.

A study carried out by Larsson (2002), has explored possible modifications to external window designs. According to Larsson (2002), the current trend in the reduction of heat loss at the base of building components has resulted in a number of important modifications to window design (Larsson and Moshfegh, 2002). These improvements have resulted in a higher surface temperature on the inner pane of the windows and a considerably lower downdraught, thereby creating an opportunity to design an unconventional natural ventilation and heating system (Larsson and Moshfegh, 2002).

Another study by Askar et al. (2001) has investigated ways in which to reduce energy demand in hot climates in the Middle East through the efficient design of external windows (Askar et al., 2001). They propose triple glazing to minimise solar radiation transmission from the ambient environment. Moreover, this triple glazing system can maintain adequate levels of natural lighting inside the building.

Concerned by the influence of window size on energy consumption, Persson et al. (2006) note that minimising the size of south facing windows, while increasing the size of northerly oriented windows, influences the energy consumption and maximum energy-load needed to maintain internal temperature comfort. Their results indicate that while energy efficiency influences ‘cooling’ in the summer, it does not significantly influence heating energy in the cold season (Persson et al., 2006). Therefore, they conclude that the enlargement of windows facing north would be of benefit, as they also improve lighting (Persson et al., 2006).

Karlsson, J. and A (2001) have investigated cooling and heating energy requirements based on the values of thermal emittance for architectural external glazing. They have studied the importance of low emittance values in three different climatic conditions, using two types of building (sensitivity for small changes in the emittance) (Karlsson and Roos, 2001). They have found that, variations in values result only in very small changes in energy performance (Karlsson and Roos, 2001). In detail, they state that, by reducing thermal emittance by 2% to 3% and the solar radiation energy transmittance by 2% to 3%, the energy performance of external windows will be made worse if the residential building is south facing (Karlsson and Roos, 2001).

In order to reduce the impact of solar heat and slow down the heat transmittance from the outside to the inside through glazing, insulated glazing was reportedly the best option for external windows. Many techniques can be used to improve the efficiency of external glazing in terms of reducing buildings' energy consumption. Recently researchers have illustrated energy performance using different multiple panes of glazing in external windows (Manz, 2008, Bahaj et al., 2008).

It is common to use a system of double glazing in external windows in buildings today, but the insulation performance of such a system is effected by many factors, including, (a) type of glass used, and (b) the inclusion of a thermal breaker in the frame (Song et al., 2007). There have been many attempts to improve the efficiency of the insulation performance of double glazing systems; such as, using a low-e coating on the glass surface; filling the gap between the panes of glazing in the windows with gas, inserting a thermal breaker made of polyurethane (Song et al., 2007), sealed-air, coatings, evacuation, phase change materials and airflow (Chow and Li, 2013). Song et al. (2007) reported that using insulation "made of thermally broken aluminium and thick walled plastic" will raise the temperature of the lowest inner surface substantially and satisfy required minimum temperature (Song et al., 2007).

In a study, Oliveira Panão et al. (2013) discussed the minimum amount of energy that would be required by near Zero-Energy Buildings (nZEB) in Mediterranean domestic buildings. They found that there is a direct correlation between the thickness of thermal insulation and the energy efficiency of the adopted solutions. Moreover, they specified the thickness of such insulation to be between 0.04 and 0.06 m. (Oliveira Panão et al., 2013). Also the researchers noted that double glazing is one of the most important energy saving solutions and asserted that its thickness should be 6/16/6mm, according to U-values. Finally, they discussed what level of energy consumption should be used in a near Zero-Energy Building and concluded that the energy demand is strongly dependent on the primary energy indicator assumed, which could significantly differ from country to country.

Multiple technologies have impacted energy saving as mentioned above. First, “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). In addition, using an advanced low-e coating in the external glaze, can reduce the solar heat exchange between glazes significantly (Singh et al., 2008). In different climatic conditions, it is necessary to place a coating on a suitable surface to decrease indoor heat gain (Chow and Li, 2013). Another technique when using natural airflow in the windows, is to use double glazed windows installed with a semi-open cavity between the glazes to permit natural airflow; the thermal performance of the windows can then be improved through fluid heat removal (Gosselin and Chen, 2008).

Many studies have been conducted to address and establish the benefits and importance of the role played by glazing in maintaining comfort in the indoor climate for the longest possible duration. Studies have explored the environmental, technical, economic, and internal comfort implications of the current technologies associated with emerging glazing, for the energy conservation of highly glazed buildings in hot climate conditions in the Middle East, which is one of the world’s harshest climates (Bahaj et al., 2008). Predictions have been made involving two examples of buildings, through the employment of thermal simulations to assess the influence of electrochromic glazing, holographic optical elements (HOE), aerogel glazing and thin film photovoltaics (Bahaj et al., 2008). After assessing the potential for reductions in cooling demand, their study of fixed glazing concluded that reflection in the form of HOE can be expected to minimise the comparable air conditioning energy use of buildings. It is claimed that light transmission in this kind of glazing would be approximately 85% of the equivalent standard (low-e glazing) solution applied. The more significant air conditioning load reduction can be attributable to the lower light transmission (Bahaj et al., 2008).

## 2.5 Renewable Energy

Renewable energy for the operation of buildings is one of the most important elements in sustainable architecture. This aspect is heavily dependent on local climate, as well as on the availability of the natural resources, such as solar radiation and wind energy.

Developing and designing with the distribution of suitable technologies for renewable energy is essential to meet the increasing energy demand for both the growth of the economy and to improve the quality of people's lives (Sathaye J et al (2011) cited in (Kandpal and Broman, 2014). Developing renewable energy technologies and disseminating them on a large scale has been the priority in a large number of countries around the world, in order to promote sustainable options and insure that environmental energy supply can meet energy demands (Kandpal and Broman, 2014). Historically, in the mid-1970s, considerable progress was made in terms of renewable energy, such as; wind energy, solar radiation energy through (photovoltaic) and thermal applications (Arent et al., 2011, Manzano-Agugliaro et al., 2013, Gross et al., 2003).

However, the recent trend toward energy management in the residential sector of the smart grid paradigm involves: (a) distribution renewable generation, (b) distribution energy storage possibilities, and (c) demand-side load management. Adoption of multi-generation systems to generate renewable energy results in significant benefits in terms of higher energy efficiency; minimising $CO_2$ emissions rates and enhancing the economy (Chicco and Mancarella, 2009).

In Saudi Arabia, there is huge potential for using renewable energy resources naturally, especially in view of the availability of solar radiation energy. Despite the availability of natural energy resources, however, the energy that is generated (in the form of electricity) in Saudi Arabia is mostly from burning fossil fuels. Natural resources are yet to be exploited in a meaningful way on Saudi Arabia, although many previous studies (since the 1970s) have presented the potential for wind and solar energy in the country (Alrashed and Asif, 2012).

This section will discuss recent studies that have been conducted into the use of natural resources, as an alternative to burning fossil fuels. The information from these studies will be compared to highlight key findings, as well as to explain the current gaps in the literature. In light of this, this section will be divided into three main categories: (i) Solar Energy; (ii) Natural Energy resources in Saudi Arabia; and (iii) Macro Energy Generation (Figure 2.7).

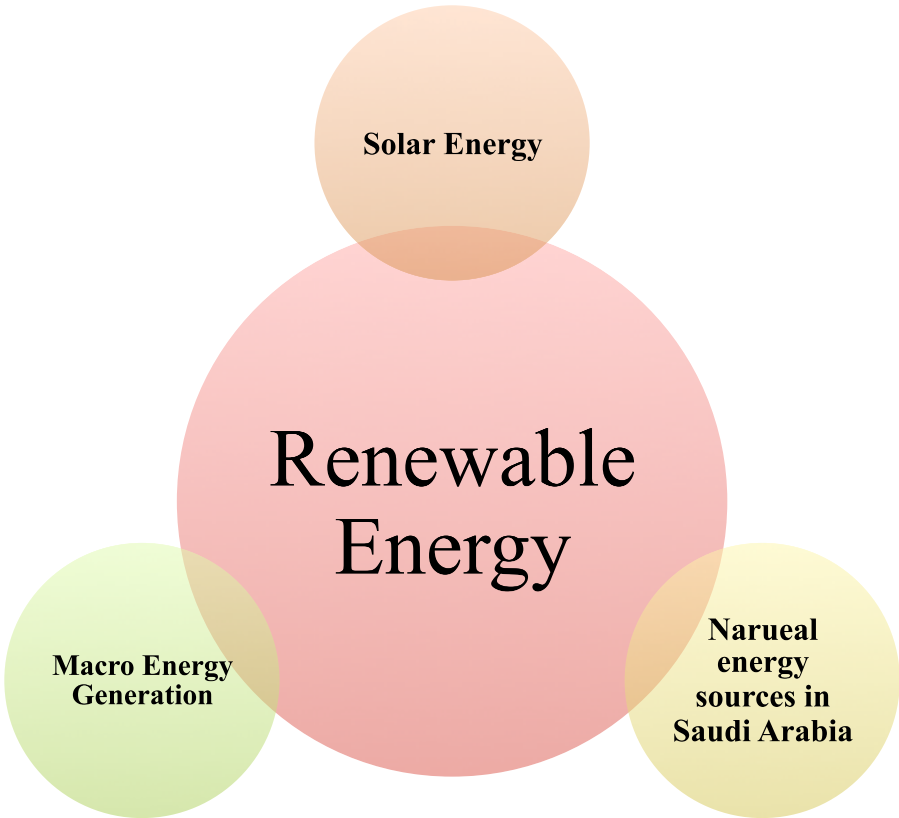



**Figure 2.7 Renewable Energy Section Structure**

### 2.5.1 Solar Energy for Buildings

Passive solar design techniques have been practiced for thousands of years; they were essential prior to the development of modern mechanical cooling or heating (Chandel and Aggarwal, 2008). When designing passive solar buildings, it is important to consider the local climate conditions. Hence, the scientific design of passive solar buildings is based on factors that include local climate, solar heat gain or loss and human thermal comfort (Hastings, 1995)

Rakoto-Joseph et al. (2009) observed that a potentially effective solution to climatic constraints can be provided by vernacular architecture, demonstrating that there is more than one approach to meeting the same climatic constraint (Rakoto-Joseph et al., 2009). Zhai and Previtali (2010) added that buildings have an important influence on natural resources and the environment, having identified efficient constructions using the techniques of vernacular architecture that are characteristic of enhancing building performance (Zhai and Previtali, 2010).

According to Delisle and Kummert (2014), in the near future (the next 5 years), within the solar industry, building integrated photovoltaics will become one of the quickest growing segments across the world (Delisle and Kummert, 2014). This increase of interest in "building-integrated photovoltaics" has arisen because many countries are currently establishing specific goals related to zero energy buildings. To achieve this aim, building designs are expected to incorporate three important concepts: (i) energy efficiency; (ii) energy saving; and (iii) optimal use of technologies for renewable energy to generate electricity naturally. For this reason, building integrated photovoltaics has significant advantages; such as, it generates electricity acting as an active component of the building envelope.

The application of photovoltaic technology (PV) is most common in on-site energy generation units (small scale). Photovoltaic technology has huge benefits for consumers and utilities, but high penetration can introduce energy quality issues in the electricity network (Salvador and Grieu, 2012, Mokhtari et al., 2013c); meanwhile the main concern is an increase in voltage during the high energy generation PVs mode (Mokhtari et al., 2013b, Mokhtari et al., 2013a). This technology is flexible and applicable to countries with hot climates that have a huge amount of solar heat, such as Saudi Arabia. According to Castillo-Cagigal et al. (2011), to resolve market penetration issues, photovoltaics (PV) must achieve a balance between generation and energy demand, mainly in situations where there is a need for high energy generation, but low demand (Castillo-Cagigal et al., 2011).

It is widely recognised that on-site energy generation using PV techniques and wind energy is a "cost effective" method, that can be applied in the countryside "suburb areas" as an isolated power system (Moharil and Kulkarni, 2009). Moharil and Kulkarni

(2009) pointed out that solar photovoltaic systems provide a competitive option and are acceptable to people in terms of commercial operation and quality of energy supply (Moharil and Kulkarni, 2009). The strategy of vertical facades is an efficient renewable energy technique to consider. A study was conducted by Ordenes et al. (2007) to discover the impact of domestic building integrated photovoltaics on energy consumption. They analysed multi-family houses in multiple locations (three different cities) in Brazil. They found a large amount of energy can be generated through vertical facades (Ordenes et al., 2007).

Employing a Photovoltaic panel (PV) system on a roof top, or using other renewable energy sources normally creates a balance between consumed and generated electrical energy, thus achieving a zero energy building (Fong and Lee, 2012). In addition to their environmental benefits, photovoltaics can also have aesthetically pleasing effects. A study of surveys conducted by building professionals and architects points out that the integration of a PV system into a building facade can improve its features (Munari Probst and Roecker, 2007).

Garcia et al. (2002) outlined potential energy reduction and noted that more efficient performance is achievable with the careful use of different passive solar strategies, such as: (a) skylights; (b) clerestory roof windows; and (c) roof monitors, as well as intelligent element measures on the roof. The implementation of solar passive strategies can significantly reduce heating load and improve ventilation and lighting in spaces where there is no equator-facing façade (Garcia-Hansen et al., 2002). In greater detail, the solar saving fraction attained through the use of the different strategies differs for clerestories, but returns an average of 43.16%, compared to 41.4% for roof monitors and 38.86% for skylights in a glass area of 9% across a floor area (Garcia-Hansen et al., 2002).

Davidsson et al. 2010 developed and evaluated building-integrated multifunctional PV/T solar windows, based upon a construction of PV cells laminated on solar absorbers and placed in a window behind the glazing (see Figure 2.8). They found that a solar window produces about 35% more energy in the form of electricity per unit cell area every year, compared with a vertical flat PV module (Davidsson et al., 2010).

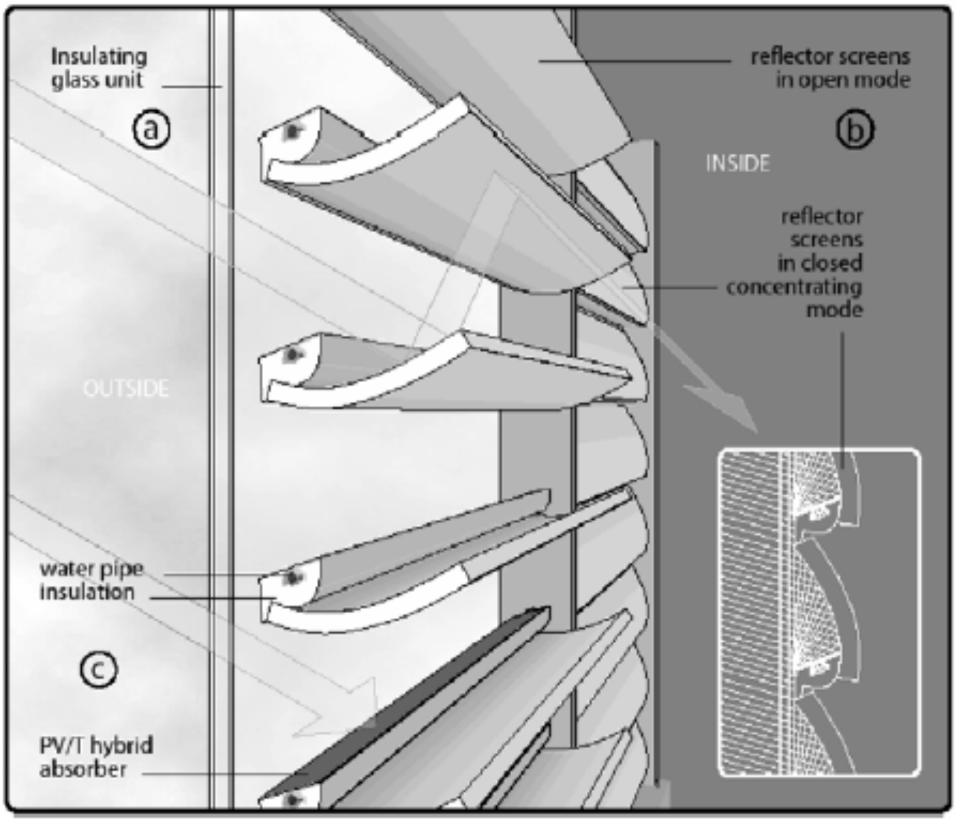



**Figure 2.8 Solar Absorbers Placed In A Window Behind The Glazing (Davidsson et al., 2010)**

In regard to solar collectors, many recent studies have demonstrated the efficiency of solar collectors; such as (Pillai and Agarwal, 1981, Liu et al., 2007). According to Zhai et al (2008) "*By the end of 2005, a total of over 60,000,000m² solar collectors have been put into use nationwide. They are installed with the main purpose of hot water supply in residential buildings.*" (Zhai et al., 2008). First, Pillai and Agarwal (1981) demonstrated a linear relationship affecting solar collector efficiency and the absorptance of the absorber surface (Pillai and Agarwal, 1981). Moreover, in discussing solar collector efficiency Liu et al. (2007) confirmed the significance of the better absorptivity of the absorber surface (Liu et al., 2007).

Pavlou et al. (2009) found that the collector surface should have as high an absorptance as possible, in order to ensure that it will affect the performance of the solar chimney. They noted that the effect of the absorptivity of the external glazing of the window on natural ventilation was approximately insignificant (Pavlou et al., 2009) cited in (Khanal and Lei, 2011). Another study was conducted by Tsoutsos et al. (2003), who reported that energy saving solutions can be offered technically by solar collectors used in combination with an adsorption chiller (Tsoutsos et al., 2003).

Anderson et al. (2009) have studied the design of a novel building, as integrated of a photovoltaic (PV) thermal solar collector to generates electricity. The study shows that photovoltaic cells with a supporting structure not only work with great efficiency but also have a significant impact of the thermal and electrical efficiency of the building (Anderson et al., 2009). The study also argues that a building integrated photovoltaic solar collector (BIPVT) is cost effective: it eliminates the costs of a supporting structure and can be made of lower cost materials without a major decrease in performance (Anderson et al., 2009). Conversely, a hybrid PVT system was examined by Chow et al. (2006), who found that the system was able to extend the PV application for housing purposes (Chow et al., 2006).

### 2.5.2 Renewable Energy Sources in Saudi Arabia

The topic of renewable energy has attracted considerable attention in the Middle East because of the climate and amount of sunshine in the region. Alnatheer (2006) provides an evaluation of the environmental impact of electrical system expansion in the Kingdom of Saudi Arabia. He demonstrates how renewable energy and energy-efficient sources can be used to generate clean and optimized energy (in the form of electricity) (Alnatheer, 2006).

Shafiqur Rehman et al. (2007) have studied the distribution of radiation and sunshine by duration across Saudi Arabia, finding a marked difference in solar radiation between different regions: from 1.63MWh/m$^2$ yr–1 at Tabuk (a northern region) to 2.56MWh/m$^2$ yr–1 at Bisha (a southern region). They add that Photovoltaic (PV) technology has been proven to be a simple and effective means of generating electricity through solar energy (Rehman et al., 2007). A more specific example of the exploitation of natural resources has been provided by Ali et al. (Al-Ali et al., 2001), who demonstrated the functioning of an automated irrigation system by means of PV modules.

The use of solar radiation for electricity generation in Saudi Arabia has been growing since 1960 (Huraib et al., 1996). A study was undertaken by Shafiqur Rehman et al. (2007) to analyse the distribution of solar radiation and sunshine period in the Kingdom of Saudi Arabia. The researchers placed grid connected PV panels of 5MW capacity in various locations across the country measured their energy production and their economic benefits (Rehman et al., 2007). They found that, annually, more than 2.0 MWh per m² of solar heat falls on the average horizontal surface in Saudi Arabia. Table 2.4 below illustrates the details of the availability of solar radiation in Saudi Arabia (Rehman et al., 2007).

**Table 2.4 Availability Of Solar Radiation Across Saudi Arabia** (Rehman et al., 2007)

| Stn # | City | Lat (deg.) | Lon (deg.) | Alt (m) | *S* (h) | *H* (MWh/m$^2$ yr) |
|---|---|---|---|---|---|---|
| 1 | Qurayyat | 31.33 | 37.35 | 2 | 9.0 | 2.03 |
| 2 | Tabarjal | 30.52 | 38.38 | 3 | 9.0 | 1.72 |
| 3 | Sakaka | 29.97 | 40.20 | 574 | 9.0 | 1.94 |
| 4 | Tabuk | 28.38 | 36.58 | 773 | 9.1 | 1.64 |
| 5 | Tayma | 27.63 | 38.48 | 820 | 9.2 | 2.04 |
| 6 | Hail | 27.47 | 41.63 | 1010 | 9.4 | 1.91 |
| 7 | Sarrar | 26.98 | 48.38 | 75 | 8.7 | 1.66 |
| 8 | Al-Ula | 26.62 | 37.85 | 681 | 9.1 | 2.12 |
| 9 | Qatif | 26.55 | 50.00 | 8 | 8.4 | 1.73 |
| 10 | Maaqala | 26.37 | 47.37 | 450 | 8.9 | 1.78 |
| 11 | Zilfi | 26.30 | 44.80 | 605 | 8.9 | 2.04 |
| 12 | Unayzah | 26.07 | 43.98 | 724 | 9.3 | 2.00 |
| 13 | Uqtalas-Suqur | 25.83 | 42.18 | 740 | 9.1 | 2.23 |
| 14 | Hutatsudair | 25.53 | 45.62 | 665 | 9.0 | 2.15 |
| 15 | Al-Hofuf | 25.50 | 49.57 | 160 | 8.7 | 2.07 |
| 16 | Shaqra | 25.25 | 45.25 | 730 | 9.2 | 2.21 |
| 17 | Hanakiya | 24.85 | 40.50 | 840 | 9.1 | 2.21 |
| 18 | Riyadh | 24.57 | 46.72 | 564 | 9.2 | 1.87 |
| 19 | Madina | 24.52 | 39.58 | 590 | 9.1 | 2.32 |
| 20 | Dawdami | 24.48 | 44.37 | 0 | 8.8 | 2.17 |
| 21 | Derab | 24.42 | 46.57 | 0 | 8.7 | 2.26 |
| 22 | Al-Kharj | 24.17 | 47.40 | 430 | 9.1 | 2.03 |
| 23 | Harad | 24.07 | 49.02 | 300 | 9.0 | 1.71 |
| 24 | Yabrin | 23.32 | 48.95 | 200 | 9.1 | 2.06 |
| 25 | Al-Aflat | 22.28 | 46.73 | 539 | 9.0 | 2.19 |
| 26 | Khulays | 22.13 | 39.43 | 60 | 8.9 | 2.18 |
| 27 | Sayl Kabir | 21.62 | 40.42 | 1230 | 8.9 | 2.46 |
| 28 | Turbah | 21.40 | 40.45 | 1130 | 9.0 | 2.09 |
| 29 | Taif | 21.23 | 40.35 | 1530 | 8.9 | 1.98 |
| 30 | Sulayyil | 20.47 | 45.57 | 600 | 9.0 | 2.40 |
| 31 | Bisha | 20.02 | 42.60 | 1020 | 9.2 | 2.56 |
| 32 | Heifa | 19.87 | 42.53 | 1090 | 9.1 | 2.22 |
| 33 | Juarshy | 19.85 | 41.57 | 2040 | 8.5 | 1.98 |
| 34 | Modaylif | 19.53 | 41.05 | 53 | 8.5 | 2.32 |
| 35 | Al-Numas | 19.10 | 42.15 | 2600 | 7.4 | 2.21 |
| 36 | Kwash | 19.00 | 41.88 | 350 | 8.5 | 1.70 |
| 37 | Kiyad | 18.73 | 41.40 | 30 | 8.4 | 1.87 |
| 38 | Sirr-Lasan | 18.25 | 42.60 | 2100 | 8.7 | 1.84 |
| 39 | Abha | 18.22 | 42.48 | 2200 | 8.7 | 2.13 |
| 40 | Najran | 17.55 | 44.23 | 1250 | 9.1 | 2.53 |
| 41 | Sabya | 17.17 | 42.62 | 40 | 8.5 | 1.83 |

It is evident that a higher amount of solar heat (radiation) is observed in cities located in southerly regions, such as; Nejran and Bisha, as followed by the Al-Sulayyil city in the central region of Saudi Arabia. Generally all cities across Saudi Arabia have a high solar radiation when compared with other western European countries. Hence, the high availability of solar radiation across Saudi Arabia offers an opportunity to harness energy in the form of electricity through natural solar heat (Rehman et al., 2007).

Meanwhile, there are some barriers to using natural resources in Saudi Arabia. According to Alrashed and Asif (2012), despite a significant potential for solar radiation and wind energy exploitation in Saudi Arabia, these natural resources are largely ignored (Alrashed and Asif, 2012). In light of this, Alrashed and Asif (2012) highlight some of the important barriers as follows (Alrashed and Asif, 2012):

1) The consumed energy in Saudi Arabia is in the form of electricity derived from oil gas and fossil fuels, which are hugely subsidised.
2) In terms of renewable energy, there is a lack of public knowledge and awareness.
3) The cost of renewable energy technologies is high.
4) Lack of governmental initiatives for renewable energy technologies, as well as an absence of subsidies, and financial motivation to adopt these technologies.
5) Lack of a database related to the weather data in Saudi Arabia.
6) Lack of data related to the cost effectiveness of technologies to harvest renewable energy; including figures for performance, durability and reliability.
7) Lack of acceptance of the application of renewable technologies due to aesthetic considerations.
8) Lack of renewable energy technologies markets (private sector), including stakeholders and renewable entrepreneurs.

A final option for generating energy is the employment of nuclear technology, Ahmad and Ramana (2014) examined economic projections for nuclear power in the Kingdom of Saudi Arabia in comparison with other sources such as electricity, solar radiation energy and natural gas (Ahmad and Ramana, 2014). Their investigation showed that the nuclear option would not be as favorable as natural gas, even if the current low price of residential natural gas in the Kingdom were to rise significantly. They stated that, unless the price of oil fell dramatically, it would be more economical to export oil, as opposed to using it for electricity generation (Ahmad and Ramana, 2014).

### 2.5.3 Macro Energy Generation

Wind energy has been acknowledged as a significant natural energy resource worldwide (Swofford and Slattery, 2010). There has been a rapid advance in wind turbine technology and increasingly sophisticated designs are leading to an increase in the size and output of wind turbines, increasing the potential for energy generation.

Stockton (2004) conducted an economic feasibility study on a utility-scale wind farm for Hawaii in the US, arguing that this type of facility could supply electricity about 34% more cheaply than the electricity provided from burning fossil fuel (Stockton, 2004). Sperling et al. (2010) added that the feasibility of wind power projects cannot be guaranteed, and that there is therefore a tendency to exclude smaller turbines from development (Sperling et al., 2010).

Crawford (2009) conducted an investigation and analysis of greenhouse emissions and the life cycle energy use and production of two wind turbines, with particular analysis of the effect of wind turbine size on energy yield (Crawford, 2009). He stated the requirements of life cycle energy are offset by the energy generated using the energy generated during a single year of operation (Crawford, 2009). Wind turbines size is not an important factor in improving their life cycle energy performance (Crawford, 2009). It has been suggested that energy yield ratio signifies the possible energy conservation that can be achieved (Wagner and Pick, 2004, Richards and Watt, 2004). The energy yield ratio presents the number of times the energy invested in the wind turbine is paid back (Crawford, 2009).

Despite their high energy yield, however, wind farms are not always desirable. In their study Swofford and Slattery (2010) demonstrated that the closest areas to a wind farm will show the lowest levels of support for it (Swofford and Slattery, 2010). On the other hand, the farthest areas from the wind farm show much stronger support of wind energy. In addition, Groothuis et al. (2008) claimed that there is an individual argument opposing wind energy projects, because of external disadvantages, such as the impact on the visual landscape and noise (Groothuis et al., 2008). Righter (2002) found that wind turbine technology, as currently in use to produce electricity, is simply too visible and disruptive (Righter, 2002). Swofford and Slattery (2010) have researched the public's attitude to wind energy generation, in northern Texas, US (Swofford and

Slattery, 2010). They used a questionnaire survey as an approach to address the physical and environmental characteristics and perception of wind energy generation. They found an overall concern for the environment but a negative attitude in those living close to wind farms (Swofford and Slattery, 2010).

Low cost and the flexibility of energy production can play an important role in renewables development. According to Warren et al. (2005), the acceptance and continued development of wind energy generation is linked to low costs, and available energy production (Warren et al., 2005). Righter (2002) agrees that this system is too valuable to overlook, particularly in countries where there is an excess of wind energy (Righter, 2002). Warren et al. (2005), provided evidence which supports a positive relationship between the degree of acceptance of this technology (wind farm) and location; claiming that the phenomenon of NIMBY (Not in My Yard) does not fully explain variations in public attitudes about wind farms (Warren et al., 2005).

## 2.6 Summary

This chapter presented the findings of studies conducted in different locations across the world, and in hot climates including Saudi Arabia. First, it focused on the topic of building form and reviewed optimal designs and techniques that could contribute to energy conservation, especially in hot climates. Second, it reviewed various studies conducted in relation to efficient house envelope designs, and renewable energy technologies in different locations across the world. Many suitable techniques have been reviewed, while some require adapting to focus on the Saudi Arabian context and climate.

Therefore, this chapter has Identified techniques and design strategies that when appropriately modified could be beneficial in view of the Saudi Arabian climate. The review has collated, (a) recent findings in this field as a database for the researcher, (b) identified which strategies and techniques can be developed and adapted to the climate of Saudi Arabia, and (c) supported the researcher to develop and establish a low carbon domestic design framework for the Saudi Arabian climate, context and cultural requirements.

# Chapter 3 : Research Methodology

## 3.1 Introduction

This chapter will present a detailed account of the methodology that was designed for this study to ensure that its aims have been adequately addressed. The following structure will be utilised: (a) Introduction, (b) research design methodology and (c) research stages and descriptions (Figure 3.1) and then research flowchart and summary. The first category will be used to define and clarify the basic concepts and terms pertaining to the methodology of this research. The second section will present the selected research roadmap and clarify the methodology that has been designed to answer the established research questions and reach the main aim. The third and final category will present the specific research method or technique that was used in each stage and explain their suitability and results.

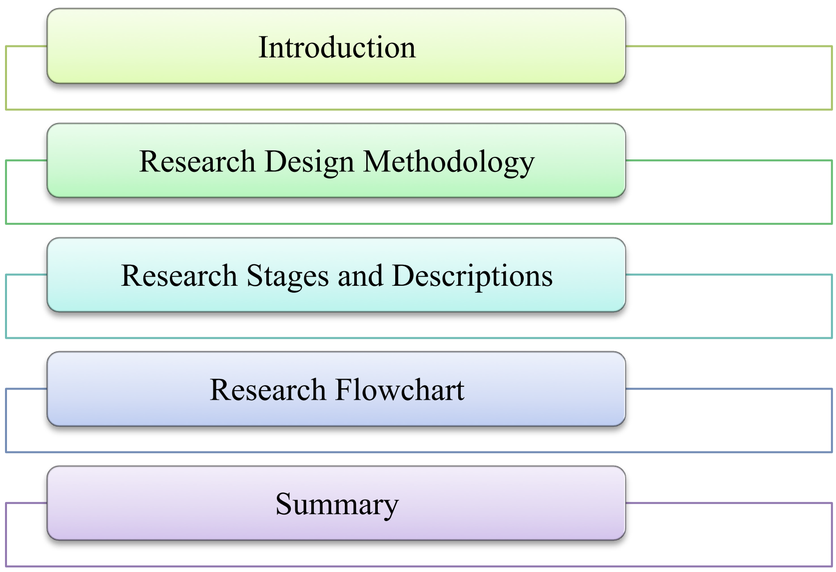



**Figure 3.1 Methodology Structure**

Research, seeks to contribute to the body of knowledge within its field through (a) study, (b) comparison, (c) observation and (d) experimentation (Kothari, 2004). Essentially, then research can be described as the use of a systematic method and objective in order to search for knowledge or to determine a viable solution to a particular problem (Kothari, 2004).

For the actual implementation of the above process, especially in the social sciences, however, the researcher relies on theoretical principles and beliefs that fundamentally influence the research process and could be composed in what is called a research paradigm. According to Jonker and Pennik, a research paradigm constitutes a framework of beliefs and assumptions about the way in which the world is perceived which, in turn, informs and guides the behaviour of the researcher (Jonker and Pennink, 2009). Although the underlying research philosophy generally remains implied rather than explicit in most research, these principles can profoundly affect the actual practice of research (Jonker and Pennink, 2009). Pragmatic management of research, therefore, relies upon recognition and questioning of the chosen paradigm, in order to understand the way in which the work is undertaken and the phenomena that frame it (Berry and Otley, 2004).

The adoption of a research paradigm requires due consideration to be given to a number of important practical considerations (Saunders et al., 2009). As illustrated in the diagram (Figure 3.2), the development of a research project requires a series of theoretical choices that are guided by a specific view of the relationship between knowledge and the research progression itself (Saunders et al., 2009). For example, the approaches, strategies and methods ( see Figure 3.2) that have been chosen may vary and so will the views of researchers on what is significant or valuable. Despite their multiplicity, however, the above choices are not arbitrary; instead they are made so as to maintain the theoretical consistency of the research (Saunders et al., 2009).

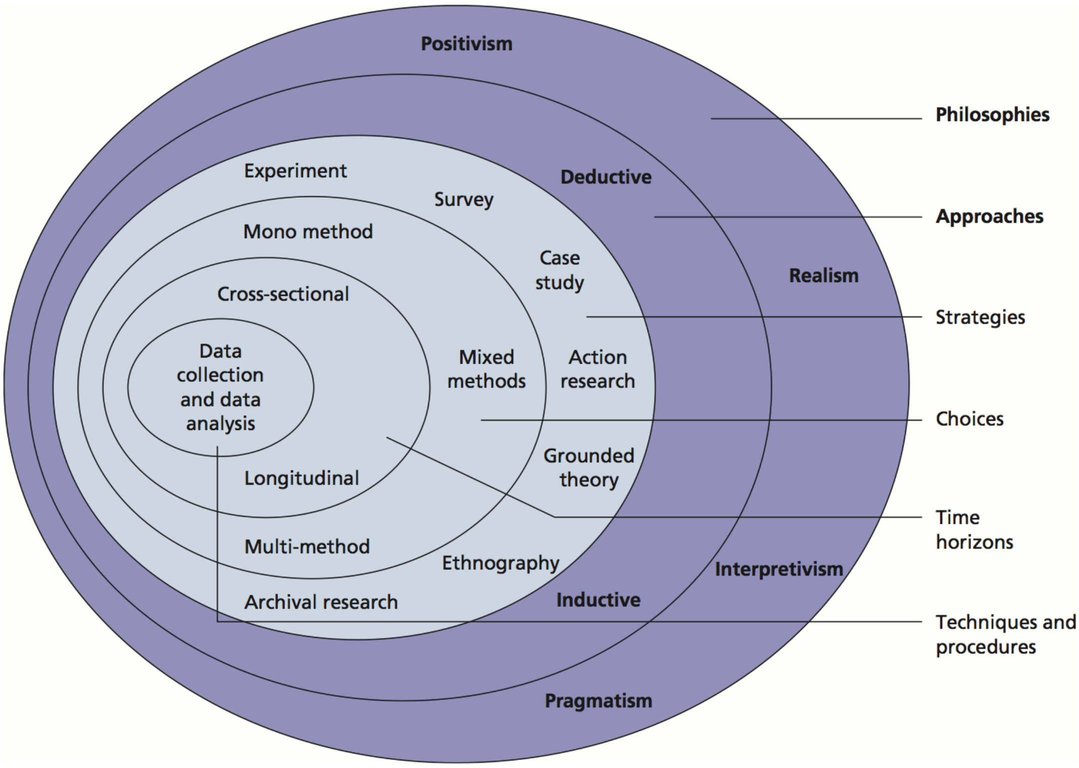



**Figure 3.2 Structure Of Research Philosophy (Saunders et al., 2009)**

At this stage, it is also important to define the term methodology and contrast it with the term method (King, 1994). Research methods can be understood to be the various techniques and procedures that are used in conducting research (Kothari, 2004), whereas the term methodology is typically used to refer to the set of rules and procedures employed to systematically solve a research problem (Kothari, 2004). Moreover, methodology can also be understood as a science of considering how the research is being scientifically performed (Kothari, 2004). In this context, however, the term methodology is used to denote, all the approaches that are employed by the researcher throughout the research process (Kothari, 2004). A distinction can also be drawn between method and technique in the context of academic research (Kothari, 2004). In general, the term *'research technique'* usually denotes the behaviour and instruments that are employed in performing the research process. These can include the tools used for saving data, making comments and expressing opinions, or even the techniques of managing records (Kothari, 2004). In contrast, research method denotes the behaviour, the instruments utilised in constructing experiments and the techniques chosen for the research (Kothari, 2004). The differences between these terms are further clarified (see Table 3.1).

**Table 3.1 Differences Between Methods And Techniques (Kothari, 2004)**

| Type | Methods | Techniques |
|---|---|---|
| **Library Research** | Analysis of historical records | Recording of notes, Content analysis, Tape and Film listening and records analysis. |
| | Analysis of documents | Statistical compilations and manipulations, reference and abstract guides, contents analysis. |
| **Field Research** | Non-participant direct observation | Observational behavioural scales, use of score cards, etc. |
| | Participant observation | Interactional recording, possible use of tape recorders, photo graphic techniques. |
| | Mass observation | Recording mass behaviour, interview using independent observers in public places. |
| | Mail questionnaire | Identification of social and economic background of respondents. |
| | Opinionnaire | Use of attitude scales, projective techniques, use of sociometric scales. |
| | Personal interview | Interviewer uses a detailed schedule with open and closed questions. |
| | Focused interview | Interviewer focuses attention upon a given experience and its effects. |
| | Group interview | Small groups of respondents are interviewed simultaneously. |
| | Telephone survey | Used as a survey technique for information and for discerning opinion; may also be used as a follow up of questionnaire. |
| | Case study and life history | Cross sectional collection of data for intensive analysis, longitudinal collection of data of intensive character. |
| **Laboratory Research** | Small group study of random behaviour, play and role analysis | Use of audio-visual recording devices, use of observers, etc. |

It can therefore be said that the term 'methods' is more general and is the aspect that refers to the generation of techniques (Kothari, 2004), and therefore discussions of research methods are generally understood to involve research techniques (Kothari, 2004).

The following sections will describe the methodology that was selected in order to arrive at the aims of this research. The selected methods and stages will be presented here in a sequential form in order to create a coherent roadmap (research design) that clearly illustrates the manner by which the afore mentioned research questions were addressed and answered. In addition, the obstacles faced by this investigation will be examined here. One of the challenges faced in this research is the multiplicity of research questions or objectives that had to be considered in order to respond to the main aim of this research. Consequently, the methodology presented here was designed in such a way that each stage has a specific method and technique in order to ensure that the established research questions are appropriately addressed. Therefore, this chapter describes the four main stages of this study and the corresponding qualitative or quantitative method that was employed to respond to the individual aim of each stage.

## 3.2 Research Design Methodology

The research needs to be divided into multiple stages to meet the main research aims and objectives. Each stage will require a specific and different approach to answer a specific research question and fulfil the specified objectives. Firstly, it is necessary to identify those factors influencing energy consumption in the domestic sector in Saudi Arabia. This approach requires a public survey analysis for this purpose. Secondly, it is necessary to pursue an additional approach, to identify the physical factors influencing energy consumption in the domestic sector and to analyse authentic cases based on the different climatic conditions in Saudi Arabia. Therefore, a site visit was added as part of the case study, to meet the other objectives and answer some of the research questions. Thirdly, it is important to employ a new approach and method to establish a framework reflecting the factors identified in the first and second stages. This new approach will investigate and analyse the most efficient and effective design techniques and strategies as they affect the Saudi Arabian climate, and cultural context. Finally, it is necessary to validate the framework and answer the final research questions. This will require the conducting of an additional approach employing a simulation tools to identify which aspects of low level energy consumption can be achieved in Saudi Arabia, and to establish an energy consumption definition standard for Saudi Arabia.

As previously stated, this study is concerned with the issue of high energy consumption in the Saudi Arabian domestic sector. Therefore, it is essential to diagnose and determine the factors causing high energy consumption in existing domestic buildings. This required an assessment of: (a) average energy consumption in Saudi Arabian domestic buildings; (b) the architectural style of housing and how homes are designed in Saudi Arabia; and (c) the cultural image and socio-cultural blockers that hinder the widespread adoption of sustainable homes in Saudi Arabia, as well as the ways in which culture can affect architectural design. In order to examine these diverse issues in depth, multiple approaches were employed, through a mixed methodology approach. Each method was designed and integrated in order to answer one or more specific research questions. Furthermore, both qualitative and quantitative approaches were utilised in order to combine deep analysis with a clear statistical image of the current situation. The purpose of this stage was to determine the severity of the problem of high energy use in the Saudi domestic sector and identify the factors causing the problem. Two separate stages were utilised to diagnose the current problem of high energy consumption in Saudi Arabia.

- **Firstly**: in order to diagnose and investigate the degree to which the problem of high energy consumption exists and to identify the factors contributing to it, it was necessary to employ an investigation approach. This involved: (a) a survey analysis of the public and their perceptions, in order to identify statistically significant corroborating data (i.e. the architectural style, area and type of their dwelling, energy consumption patterns, occupant behaviours, public perception of sustainable homes and socio-cultural barriers that prevent the establishment of sustainable homes in Saudi Arabia); and (b) physical visits to specific sites in order to identify the design weaknesses that are causing high energy consumption. These structures were assessed for design weaknesses with regards to poor design of the building (form) and the construction materials selected for the house envelope (fabric). These visits were necessary because a survey could not have provided the required, empirical data concerning the physical properties of the sites under consideration.

A comprehensive study of the energy consumption also requires concrete data on $kWh/m^2$ usage in existing occupied homes across Saudi Arabia. The layout plans of these structures also need be investigated with regards to architectural design weaknesses, potential issues with house envelope design and onsite renewable energy strategy used, if applicable. Identification of these issues required the use of simulation software tools to model each home individually. Therefore, site visits, modelling and simulation for homes chosen from locations across Saudi Arabia comprise an important aspect of this research. The accuracy of the overall study findings was reinforced by this collected data on average energy consumption patterns in $kWh/m^2$ for existing homes, the architectural design style, the construction materials (form and fabric), and the use of on-site renewable energy.

- **Secondly**, having diagnosed the energy consumption problems, this study has attempted to propose constructive solutions for retrofitting existing homes, and to develop a framework for the design of new, low energy housing in Saudi Arabia. As explained in the introduction, the main aim of this research is to support the establishment of low energy homes in Saudi Arabia. This requires: (a) establishing a low carbon domestic design framework that guides and supports architects, civil engineers and building professionals in the design of low energy housing, with due consideration for the hot climate and cultural requirements of Saudi Arabia; and (b) designing and validating an energy consumption definition standard (in $kWh/m^2$) that is applicable to the specific climate and cultural requirements of Saudi Arabia. This necessitated the use of supplementary research, comprising two separate but complementary approaches: approach one involved the development of a framework for designing low energy homes in Saudi Arabia, with recognition of the current problems, cultural barriers and climate conditions of the country; and approach two, which proposed, modelling and validating different designs of housing prototypes for Saudi Arabia.

In approach one: a low carbon domestic design framework was established to design low energy housing in Saudi Arabia on the basis of occupant needs, cultural requirements and local climate conditions. This required the use of two methods: consultation with experts in this field drawn from the nation that facilitated the development of a framework for sustainable housing in Saudi Arabia. In approach two: having established a framework in approach one, it was necessary to design and validate low energy homes for the specific Saudi Arabian climate, context and cultural requirements. This phase attempted to prove that a lower level of energy consumption can be achieved and is viable, despite such demanding conditions, and therefore, an energy consumption definition brand (in kWh/$m^2$) can be determined for Saudi climates.

It becomes apparent, then, that for the purposes of this study, a mixed method approach (Denscombe, 2008, Johnson and Onwuegbuzie, 2004) was required; that is an approach that combines qualitative and quantitative methods (Kelle and Erzberger, 2004, Morgan, 2007). According to Johnson et al (2007) the "*Mixed method approach is becoming increasingly articulated, attached to research practice, and recognized as the third major research approach or research paradigm, along with qualitative research and quantitative research*" (Johnson et al., 2007). The mixed method approach involves the use of multiple research techniques, typically including qualitative and quantitative approaches, in order to generate more comprehensive data and analyses of a research question (Johnson et al., 2007).

The combination of the two approaches has proved quite fruitful in various fields (Saunders et al., 2009). In Management and Business research, for example, both quantitative and qualitative approaches are commonly utilised in order to incorporate data of varying natures both in the collection and analysis stages (Saunders et al., 2009).

Generally, the two approaches enable research in which both numerical and lexical data are taken into consideration (Saunders et al., 2009). Essentially, the quantitative method is typically employed for data collection techniques e.g. surveys using questionnaire distribution techniques or data analysis processes that use or generate numerical data, such as statistics or graphs (Saunders et al., 2009). In contrast, qualitative approaches are generally utilised for the techniques of data collection like interviews, which use or generate lexical or visual, non-numerical data (Saunders et al., 2009).

The term mixed methods is commonly used to denote a fusion of both qualitative and quantitative techniques for data collection and analysis (Saunders et al., 2009). This combined approach enables the use of multiple techniques, either simultaneously or sequentially, as required by the needs of the research in question (Saunders et al., 2009). Typically, qualitative and quantitative world views are involved at the research approaches stage, with quantitative data being analysed by quantitative techniques and qualitative data being analysed qualitatively (Saunders et al., 2009).

Researchers could consider the use of the interview technique during the illustrative phase to better understand the key issues before they design and distribute their survey to gather illustrative data. Through this approach, they are more likely to ensure that they are able to address the most important issues from the beginning of their work and therefore optimise the relevance of their findings (Saunders et al., 2009).

This approach recognises that certain established questions are better approached from a quantitative perspective, whereas others benefit from qualitative techniques. Mixed methods research has become an increasingly articulated, involved practice, to the extent that it is recognised as the third main research methodology or research paradigm (Johnson et al., 2007). It has been argued that there is not a single standard of differentiation for mixed methods research; instead many approaches are deemed to be valid, in both a pure, narrow sense and in a broader or comprehensive sense. Moreover, as an essential definition is still to be determined, dialogue and social construction of a definition remains important, even though these definitions are likely to change frequently and fluidly over time, as research paradigms evolve (Johnson et al., 2007). In a broad sense, the term 'mixed methods' enables the use and integration of diverse issues and strategies in the collection of data, such as questionnaires, observations and interviews, with research tools like experimentation and ethnography (Johnson et al., 2007).

The main aim of research is to identify a given problem and offer a solution, taking into account the available data and the relationship between that data and the problem gaps. In order to achieve this broad aim, three different categories of research methods are available (Kothari, 2004):

- Methods concerned with data collection. As such, they are typically employed in cases where the available data are insufficient to identify a viable solution;
- Statistical techniques utilised to establish relationships between the data and the unknowns;
- Methods used to assess the validation and accuracy of research finding

## 3.3 Research Stages and Descriptions

Having presented an overview of the study context situated and discussed the emergent design requirements, this section will provide a detailed examination of the four approaches chosen to answer the research questions. These are: investigate the problems, determine the intensity of the problems in Saudi Arabia, establish a design framework, and design low energy homes in Saudi Arabia. The first two stages will focus on investigation and diagnostic studies, uncovering the factors influencing energy consumption in the domestic sector in Saudi Arabia (Figure 3.3). Each approach will introduce its own individual method and technique to meet particular objectives. Stage one of the research is provides the first step and approach (public survey) to diagnosing the factors influencing high energy consumption, while the second stage of the research is added as an additional approach to diagnose the physical factors influencing energy consumption in the housing sector in Saudi Arabia. The other two stages will provide a sustainable domestic low energy design framework for sustainable homes and offer different design prototypes (Figure 3.3). This section is divided into four parts (see Figure 3.3), each of which describes the technique or method utilised and justifies its use where necessary.

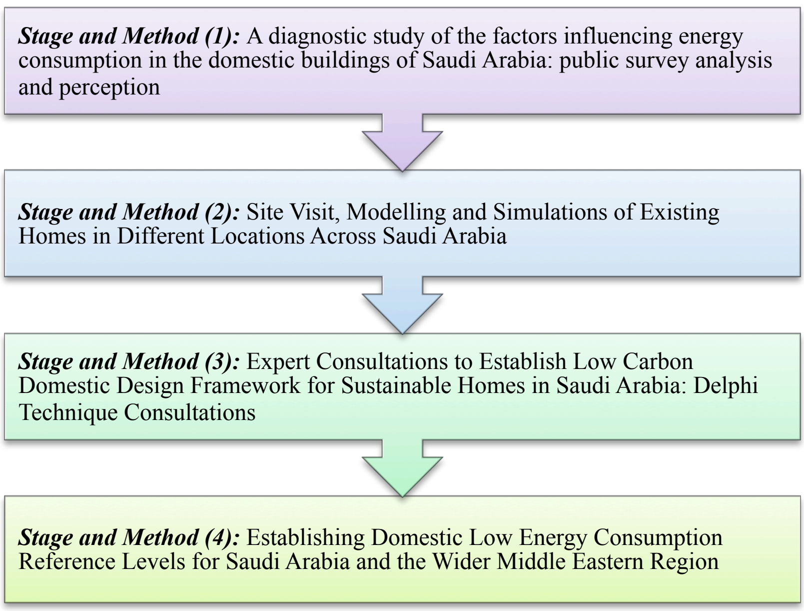



**Figure 3.3 Research Stages And Used Methods**

### 3.3.1 Stage One: A Diagnostic Study Of The Factors Influencing Energy Consumption In The Domestic Buildings Of Saudi Arabia: Public Survey Analysis And Perception

To meet the needs and requirements of the people in Saudi Arabia, it was important to assess the current level of knowledge of people regarding sustainability, energy conservation in domestic buildings, as well as their knowledge of the economic and environmental importance of having low energy housing in Saudi Arabia**.** Furthermore, it was also necessary to identify the socio-cultural barriers that hinder the construction of sustainable, low energy homes in Saudi Arabia and to examine the factors and public requirements that lead to such high energy consumption in the domestic sector.

This stage investigated the factors causing high energy consumptions in Saudi domestic buildings. These factors were related to the architectural design style, such as building size, average number of rooms per unit, the cooling and heating system (HVAC) employed and the cultural effects on architectural design. Finally it was also necessary to identify the ways in which people in Saudi Arabia operate their homes in order to determine an average user profile for domestic buildings.

In order to diagnose the factors influencing energy consumption in the domestic sector in Saudi Arabia, a public survey and perception analysis method was selected as the main approach. Surveys are the most popular method used to collect data; as stated by (Huang, 2006), survey approaches are techniques of data collection that aim to discover exact estimations of the prevalence of significant variables. This stage addresses the following overarching research questions:

- Objective one: Identify the factors affecting energy demand in the domestic sector in Saudi Arabia.
- Objective two: Identify the socio-cultural blockers hindering the adoption of sustainable homes and the implementation of large scale retrofitting programs.
- Objective three: Identify the level of public awareness and engagement with sustainable homes principles.
- Objective four: Identify the energy policy and regulatory framework in Saudi Arabia.

A quantitative methodology was used to address the above research questions. Comprehensive information related to building design, site characteristics, socio-cultural aspects, and public perception are needed and were sought from people of different ages, education levels, and locations, as elaborated below. That is survey questionnaire was designed, piloted, and distributed to people of different ages, education levels and locations in order to obtain information related to building design, site characteristics, socio-cultural aspects and public perceptions about sustainability across Saudi Arabia.

#### 3.3.1.1 *Questionnaire Description*

Based on these considerations, the questionnaire was divided into four main categories: (i) eliciting the main factors leading to high energy consumption patterns in dwellings across Saudi Arabia; (ii) understanding levels of reliance upon, and use of, heating, ventilation, and air conditioning (HVAC), (iii) exploring people's perceptions of sustainability and their preparedness to invest in sustainable dwellings in the future and to retrofit their existing homes, and (iv) identifying cultural barriers – such as faith, social status or position in society – that affect architectural design in Saudi Arabia, preventing the development of sustainable dwellings. Both English and Arabic languages were used in the questionnaire; a sample of the questionnaire can be seen in Figure 3.4 below

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التصورات الإجتماعية بخصوص المباني السكنية المستدامة المرشدة للطاقة في المملكة العربية السعودية
Public perceptions regarding sustainable dwellings in Saudi Arabia

* 26. ضع وجهات نظرك حول المواضيع التالية المتعلقة بالعادات والتقاليد الإجتماعية الإسلامية في السعودية
Please indicate your point of view on the following socio-cultural issues:

| | لا أوافق بشدة (Strongly disagree) | لا أوافق (Disagree) | محايد (Neutral) | أوافق (Agree) | أوافق بشدة (Strongly agree) |
|---|---|---|---|---|---|
| هل توافق على أن تكون غرفة الضيافة واحدة ومختلطة بين الرجال والنساء في المنزل؟ (Would you agree to having only one guest room for both genders?) | ○ | ○ | ○ | ○ | ○ |
| هل توافق على أن تكون غرفة الطعام واحدة ومختلطة بين الرجال والنساء في المنزل؟ (Would you agree to having one dining/sitting room for both genders?) | ○ | ○ | ○ | ○ | ○ |
| هل توافق على تقليل مساحة غرف النوم على أن تتناسب مع عدد الأفراد في الغرفة؟ (Would you agree to having bedroom appropriately sized to fit the needs of occupant?) | ○ | ○ | ○ | ○ | ○ |
| هل توافق على أن تكون المنازل بأسطح مائلة بدلا من الأسطح المسطحة؟ (Would you agree to having a sloping roof instead of a flat roof?) | ○ | ○ | ○ | ○ | ○ |
| هل توافق على تقليل مساحة المنزل لهدف ترشيد الطاقة؟ (Would youagree to living in a smaller house in order to reduce energy demands?) | ○ | ○ | ○ | ○ | ○ |

* 27. هل حجم ومساحة المنزل يعكس المكانة الإجتماعية؟ (Do you regard the size of someone's house as a symbol of the person's status or stature in society?.)

○ نعم (Yes)
○ لا (No)
○ ليست بالضرورة (Not necessary)

**Figure 3.4 Sample And Languages Used In The Distributed Questionnaire**

#### 3.3.1.2 *Sampling Techniques*

The online questionnaire distribution technique was used in this study, as it is quicker compared with a manual printed survey (Stanton, 1998, Weible and Wallace, 1998), and is also less costly (Huang, 2006). The Snowball sampling technique (Biernacki and

Waldorf, 1981) was used for large scale distribution of the questionnaires in Saudi Arabia. To access participants across all regions of the country, the survey was hosted with SurveyMonkey (www.surveymonkey.com) (Gordon, 2002). The link for the questionnaire was distributed via email to the public in Saudi Arabia. This web tool facilitates the wide distribution of questionnaires using the Snowball technique (Biernacki and Waldorf, 1981). The researcher was then able to monitor and view the responses to the survey and analyze the results.

The Snowball sampling technique was used for the large scale distribution of the questionnaires in Saudi Arabia. The snowball sampling technique is an academic approach to sampling, employed in order to allow the sampled units to promote their own data as well as other units (Frank and Snijders, 1994). This approach has been considered efficient, economical and effective (Singh et al., 2007). Moreover, the Snowball sampling method is elsewhere referred to as chain-referral or link-tracing (Illenberger and Flötteröd, 2012). This technique is employed by the distribution of a questionnaire by an author to participants, who then forward the study to others, who also forward it to attain a high participation rate. The snowball sampling enabled the authors to penetrate a high number of anonymous participants, while still recruiting and identifying informants with specific knowledge (Bird, 2009). The surveys were issued in Saudi Arabia and sent to potential participants by the main author using email and social networks, and, in turn, those participants forwarded the study to others as described in the snowball approach (Sadavoy et al., 2004). In this study, the process was repeated between April 2013 and September 2013, in stages referred to in (Goodman, 1961), until the required number of apexes had been sampled. It is worth noting that the ego-centric method is restricted to first degree associations, whereas snowball sampling creates an intricate grid (Illenberger and Flötteröd, 2012). In light of this, a direct approach is to pick random participants of different ages, genders, and educational levels from different cities across Saudi Arabia (referred to as egos), and to then enquire about their social connections or alters. This ego-centric grid sampling method detailed by Wasserman and Faust (1994) (Wasserman, 1994) creates star networks; a process that allows understanding of the relationships between egos and their alters.

### 3.3.2 Stage Two: Site Visit, Modelling And Simulations Of Existing Dwellings In Different Locations Across Saudi Arabia

The research aims of this study are reliant upon extensive data collection. Certain key information was not available through the public survey though. It was therefore necessary to investigate the energy consumption patterns for some existing occupied dwellings and analyse the findings using a simulation software tool. This was important in order to address the weaknesses of architectural design (form), house envelope design (fabric) and on-site renewable energy strategies currently used in Saudi Arabia. These weaknesses cannot be determined by means of public questioning or questionnaire distribution due to the deep analysis and expert knowledge required in terms of domestic energy consumption. It was therefore necessary to determine the technical factors (design weaknesses) leading to high energy consumption in housing stock in Saudi Arabia, whether in terms of building weaknesses (design, construction materials used, or on-site renewable energy generation if applicable) or occupant behaviour. Consequently it was deemed necessary to investigate and simulate the energy consumption patterns in several real cases (existing, occupied homes) in different locations across Saudi Arabia in order to facilitate that in-depth analyses and create accurate figures. In light of these requirements, the main purposes of this stage is to address the following overarching research objectives:

1- Objective one: Identify the design weaknesses in terms of architectural design (form) and house envelope design (fabric) that contribute to a high energy demand. This stage will also concentrate on identifying how the housing in Saudi Arabia are designed architecturally, including the choice of common construction materials used.
2- Objective two: Identify the level of energy consumption patterns (in kWh per year) for typical residential homes in Saudi Arabia, taking into account the climatic conditions (hot arid climate, hot humid climate and hot arid, mountainous region) and main energy uses.
3- Objective three: Identify the occupant behaviours and habits for those dwelling in typical housing in Saudi Arabia, examining the ways in which residents operate their dwellings for particular selected homes across Saudi Arabia.

4- Objective four: suggest possible retrofitting solutions in order to limit energy consumption for existing housing and determine optimal courses for future energy reduction through retrofitting and environmentally friendly new builds.

#### *3.3.2.1 Used approach in this stage*

For the purposes of this study, it was essential to investigate how residential buildings are designed and which construction materials are used for the building envelope (external walls, roof floor and external glaze). With this data it should be possible to address the design weaknesses leading to a higher than desired energy consumption in housing in Saudi Arabia. The insights from this should also enable this study to ascertain the extent to which energy consumption might be reduced in domestic buildings in Saudi Arabia in the future.

Consequently, a quantitative approach was selected to meet the above objectives. Real existing occupied homes in different locations across Saudi Arabia were selected, modelled and then comprehensively analysed with a simulation software tool in order to determine their efficiency in terms of architectural design (form), efficiency house envelope design (fabric) and energy consumption patterns. This simulation and analysis addressed: (a) the energy consumption patterns in domestic buildings in Saudi Arabia; (b) the weaknesses in architectural design; (c) the weaknesses of the house envelope design; and (d) the particular behaviour profile of each occupant in each property. In order to gather the data required for these assessments, site visits were conducted to multiple homes in different locations that represented a range of native Saudi Arabian climatic conditions. This process will be discussed in greater depth below.

#### *3.3.2.2 Site visit and Data collection based on climatic conditions*

Saudi Arabia has a hot, arid climate in the middle desert and north regions; a hot humid climate in the west coast by the Red sea and east coast by the Arabian Gulf; and a hot arid mountainous region in the south west. This diversity comprises a significant challenge to this study, due to the complexity of addressing these different types of climatic conditions and delivering an accurate image of each individual region.

During this stage, the study aimed to analyse the weaknesses in different houses and flats that hinder the implementation of optimum energy efficiency solutions. An attempt was also made to determine the average energy consumption in the residential sector in the hot climates across Saudi Arabia. Jeddah city was used as representative of hot humid climates, Riyadh city as an example of hot arid climates, and Al-Baha city as an example of hot arid mountainous climates (Figure 3.5).


**Figure 3.5 Saudi Arabia Map And The Three Selected Cities**

The approach used relied on an examination of 18 properties in these three cities (six properties in each of the aforementioned cities), each of which was categorised according to the architectural design and the construction materials used.

Data collection at this stage was one of the greatest challenges faced by the researcher, as highlighted in the challenges listed in the introduction chapter. The researcher managed the timescale to gather the necessary data within a limited timeframe. The data at this stage described (a) the architectural layout and construction plans for the 18 cases across Saudi Arabia, (b) utility (electricity) bills for each individual case, (c) interviews with each individual occupant, and (d) modelling of each case using IES-VE simulation software tools based on the data collected. It is difficult to collect the data officially from governmental institutes, because some of it is sensitive. Therefore, the researcher collected the data directly from householders who respected and valued the study. The selected cases reflect typical homes in Saudi Arabia. Data collection was performed across three phases by region: Jeddah region, Riyadh region, and Al-Baha region, at the end of 2012 and into 2013.

#### *3.3.2.3 Original layout plans and electricity utility bills for each case*

In the selected multiple-case study approach, various houses and flats were selected for the research. Each of the chosen dwellings was determined to be of average area representative of dwellings in Saudi Arabia. The selected houses and flats are located in different parts of each city and are currently occupied. In the site visit, it was necessary to collect copies of the official building design layout, including the construction materials plans used in the construction of these buildings.

For each case study, a set of official drawings was obtained from the Municipality. These drawings include the architectural plans, original layout, site plans, structural plans and construction plans. It was also necessary to obtain official electricity bills for each property in order to identify typical energy consumption levels in Saudi Arabia, as well as to compare expenditure in the sampled locations. Annual electricity bills were acquired directly from the occupants, providing information on the annual energy consumption registered by the meter at each property. Details of where this energy was consumed are vague, but can be investigated using professional simulation software tools.

The data provided above enables the annual energy consumption (in kWh) of each residence to be presented, investigated and discussed. In addition, this data also facilitates the identification of weaknesses of building fabric and architectural design. Information on how these buildings are operated during the year by the occupants was obtained by means of one-to-one interviews with the occupants in each selected case.

It is acknowledged that occupant behaviour is typically reflected in the energy consumption of a property. It is necessary to know how an occupant uses the rooms within their property in order to determine the exact uses of a building, which result in the annual energy consumption in kWh illustrated in the official annual bills provided. For this reason, intensive interviews were conducted with each occupant of the selected 18 homes. The interview attempted to gather data on the use periods for each room in the homes, in addition to whether or not cooling systems are used and whether other electrical devices are present. Participants were also asked whether the building is used in the same way throughout the year, and whether they have habits that might affect energy usage.

#### *3.3.2.4 Case study modelling*

Each case study was modelled, simulated and analysed using a specially chosen software tool. The following elements were taken into consideration in this process of analysis:

1- Building architectural design (form)
2- Building envelope (fabric)
3- Occupant behaviours
4- Local Climatic conditions

The official layout plans for each selected case were fully constructed without any serious modifications. According to the Ministry of Electricity, one of the conditions for supplying electricity to a domestic unit is that the landlord must provide an approval certificate from the Ministry of the Municipality confirming the building was constructed according the original approved layout plans and the ministry rules. Hence, each selected home (case) in this study was designed and constructed according to the regulations established by the housing authorities in Saudi Arabia, and the Ministry of the Municipality had already certified that no major or serious changes had been made. However, there is usually a gap between the original design and its realisation. First the layout plans present some limited data related to the architectural and construction materials found when interviewing. The systems of electricity and equipment is not shown in the plans. Moreover, some minor changes could have been made during or after the construction process, although these changes will not influence in energy consumption. Comparisons between the simulation output and the actual bills have been made to validate the models.

Furthermore, the official electricity bills presented the actual energy consumption recorded by the meter of each home investigated in this stage. However, while official architectural and construction plans provided information on the form and fabric for each home involved, data was also required on the actual purpose for energy use and the $CO_2$ emission rates for each building. Consequently, a simulation software tool was employed to create a three dimensional geometry model for each case study based on architectural design, building envelope used, occupant user profile and local climate profile. The simulation served to illustrate: (a) annual energy consumption; (b) the details of where this energy is consumed; (c) the amount of $CO_2$ emission rates; and (d) the efficiency of architectural design and building envelope that were used for each case.

#### *3.3.2.5 Use of simulation software tools IES-VE*

In order to investigate the energy consumption for each property in this stage, a software tool with which to simulate energy consumption was needed. There is a wide range of simulation software tools available which analyse energy consumption in buildings (e.g. Energyplus, DesignBuilder, TRNSYS, and IES-VE). These tools can analyse and predict energy consumption patterns in buildings in accordance with specific datasets. Over the last 50 years, the IES-VE simulation tool has evolved into a robust and reliable simulation environment (Ibrahim and Zain-Ahmed 2006; cited by (Shameri et al., 2013). IES-VE has a sophisticated energy performance assessment capability compared to similar energy simulation tools (Shameri et al., 2013).

Many related studies have used energy simulation tools, including IES-VE, for determining building energy consumption. (Al-Tamimi and Fadzil, 2011) used IES-VE to simulate energy consumption in a high-rise building to validate the potential energy reduction that could be achieved by adopting a shading device in Malaysia. The results indicate that egg-crate shading caused a significant decrease in hours of discomfort compared to other shading types (Al-Tamimi and Fadzil, 2011). Taleb and Sharples (2011) used DesignBuilder to simulate energy consumption in a domestic apartment in Saudi Arabia. They analysed energy consumption of one apartment as a case study and multiplied the results by the number of apartments in the building. They found that a potential 32.4% energy reduction could be achieved by improving the insulation of external walls and roof, together with more efficient external glazing (Taleb and Sharples, 2011). Al-ajmi and Hanby (2008), simulated the energy consumption of Kuwaiti domestic buildings. They modelled case studies of buildings by using TRNSYS. Simulation results informed the researchers about the necessary energy design solutions requiring adoption in domestic buildings, which ultimately helped enhance the national energy conservation code (Al-ajmi and Hanby, 2008).

IES-VE was chosen for the purpose of this study because of its established energy performance assessment capability compared to similar energy simulation tools (Shameri et al., 2013). This was utilised to simulate energy performance at the chosen properties in terms of hourly, daily, monthly and annual energy consumption, based on (a) their official architectural design plans, (b) their construction plans and (c) their occupants' behaviour profile.

To validate the simulation output offered by IES-VE simulation tools, a comparison between the simulation output and official electricity bills was performed for each of the 18 selected cases. This comparison was conducted on the basis of total annual energy consumption in kWh, annual energy consumption in kWh/m² and monthly energy consumption. The energy consumption according to IES-VE and the actual bills should be similar or very close. The purpose of running the simulations was to allow a comparison between the anticipated energy use and actual energy consumption, as shown on the official bills gathered, which reflect electricity use, as recorded by the electricity meters. The advantage of IES-VE simulations over actual bills is that they can inform the ways in which energy is consumed in the properties studied. IES-VE can analyse and simulate existing and new buildings at various geographical and climatic locations (IES-VE, 2009).

The uniqueness and significant contribution of the present study lie in (a) the focus on domestic energy consumption patterns in a hot climates; (b) the use of a representative multiple-case study (18 homes) in three different climatic conditions(hot arid climate, hot humid climate and hot arid mountains region; (c) identification of weaknesses leading to high energy consumption patterns locally and across Saudi Arabia, (d) provision and validation of carefully (context-based) selected retrofitting solutions that achieve a reduction in energy consumption in these selected properties; and (e) the strong potential to replicate these solutions across Saudi Arabia and beyond.

#### *3.3.2.6 IES-VE Model of each existing property*

The IES-VE modelling of the selected properties involved two stages: first, a model for each property was developed with a view to investigate and establish energy consumption patterns in the selected hot and humid climate region of Saudi Arabia; second, an energy remodelled version of these properties is developed based on the suggested energy retrofitting solutions, to validate the potential reduction in energy consumption.

- **Phase one**

For each case study (property), a three-dimensional model was constructed using IES-VE, based on (a) the actual individual design specifications, (b) the actual construction materials used, and (c) occupants' behaviour profile. The gathered drawings provided a detailed account of the architectural design features of each property, the type and area of each room, the area of each window, and the overall orientation of the building. In addition, structural and construction plans clearly indicated the type of building materials used (house envelope). These data are needed as input for the energy model of each property. An in-depth and lengthy interview was organized with the householder of each property to establish how the occupants use their dwelling. Finally, the energy model of each property was simulated to provide detailed energy consumption accounts on the basis of building design (form), construction materials used (fabric), occupants' behaviour profile and prevailing climatic conditions. It should be noted that the IES-VE simulation results also give the $CO_2$ emissions for each case study, which are derived from the type and amount of fuel used to generate the electricity consumed by the building.

The simulation of each property was therefore prepared in such a way as to yield hourly climate data and hourly energy consumption rates, and to describe the conditions that result in energy consumption peaks. The simulated results provide also the energy consumption of each individual room, as well as the variations in energy consumption between premises.

- **Phase two**

Based on the weaknesses identified in stage one, a number of possible solutions were proposed for reducing energy consumption in these properties, taking into account the local context. The properties simulated in stage one were then remodelled on the basis of the suggested retrofitting solutions and a new energy simulation was performed, using the same user behaviour profiles. The final energy simulation results of the retrofitted properties was benchmarked against the previous simulation results (before retrofitting) to validate the potential for energy consumption reduction.

### 3.3.3 <u>Stage Three:</u> Expert Consultations To Establish Low Carbon Domestic Design Framework For Sustainable Homes In Saudi Arabia: Delphi Technique Consultations

Previous sections of this research determined the level of problems causing or contributing to high energy consumption through public survey analyses. In addition, the efficiency and design weaknesses in existing Saudi Arabian homes were evaluated through site visits, modelling and simulation. This enabled the evaluation and provision of solutions for existing homes to conserve energy. This study will now focus on the establishment of a low carbon domestic design framework that will inform and guide the design of future sustainable low energy homes in Saudi Arabia, with specific reference to keeping $CO_2$ emission rates low.

This low carbon domestic design framework will support architects, developers, building professionals and civil engineers in the design of low energy homes in accordance with the climatic and cultural requirements of Saudi Arabia. This framework will therefore take into account the identified weaknesses, whether in terms of form and fabric, or in terms of consumption levels and socio-cultural blockers. This stage will pursue the creation of a low carbon domestic design framework for future sustainable homes through the following:

- <u>Objective one:</u> Collaborate with experts to investigate and develop energy saving techniques and design strategies related to architectural design (form) and house envelope design (fabric) for the specific climate and cultural requirements of Saudi Arabia.
- <u>Objective two:</u> Investigate and develop, with expert consultation, suitable strategies regarding the use of on-site renewable energy in accordance with the availability of natural sources and vernacular architecture in Saudi Arabia.
- <u>Objective three:</u> Establish a low carbon domestic design framework for the Saudi Arabian climate and culture in order to support the design of sustainable, low carbon energy homes in the future.

In order to establish an efficient low carbon domestic design framework for sustainable, low energy homes in Saudi Arabia, a qualitative methodological approach was chosen which involved a consultation with experts across the country. The purpose of the consultation was to gather expert judgments about low carbon techniques and design strategies to establish a framework that will assist design and engineering teams, including architects, in designing sustainable and low energy housing in the Saudi Arabian climate and culture.

#### *3.3.3.1 Used Method for Experts' Consultations*

The consultation with experts involved the use of the Delphi Technique designed to achieve consensus among the members of a panel of experts (Keeney et al., 2001, Landeta and Barrutia, 2011). The Delphi technique can be used as an investigation tool for expert problem solving in various fields such as: the sustainable development industry, engineering, and policy making (Landeta and Barrutia, 2011, Al-Saleh, 2009, Chan et al., 2001, Geist, 2010). Many applications of this technique have relied on online consultations with experts (Gnatzy et al., 2011).

One of the advantages of using the Delphi Technique in gathering data is subject anonymity which tends to level out the effects that dominant individuals may have within the group of experts (Klenk and Hickey, 2011). Moreover, online communication by e-mail helps maintain confidentiality.

The Delphi Technique required consultation with many different experts within three different rounds: (a) a brainstorming round to provide, assess and evaluate many different techniques and design strategies, based on experts' feedback and participation, (b) a narrowing-down round to reduce the huge number of techniques and identify the most efficient ones, based on experts' assessment, and (c) a final-rating round to assess the final individual techniques and strategies and reach a consensus in the context of the Saudi climate and culture.

#### *3.3.3.2 Delphi Consultation Plan*

An initial questionnaire was designed and developed for the first round, which included many different techniques and design strategies related to building design (architectural design), construction materials (house envelope), on-site renewable energy strategies, and cultural issues. Using the Delphi Technique, consultations with 40 experts in Saudi Arabia were carried out. These experts were appointed from different ministries and organisations related directly to the construction industry, such as: the ministry of housing, the ministry of municipality, engineering consultations, universities and construction companies.

In the first round of the consultation, the questionnaire was distributed to these experts across Saudi Arabia in different organisations. The consultations were carried out with the same experts through three phases (rounds). This section outlines the criteria for selecting experts and the plan for distributing the questionnaire. Each round will have particular objectives as described below:

- **The first round, (the Brainstorming Round),** was started by establishing a questionnaire involving many different design strategies that support the designer (architect) in designing sustainable residential buildings in hot climates (Saudi Arabia). The questionnaire is structured into four main categories: architectural design techniques, building fabric, on-site renewable energy, and socio-cultural considerations. Each expert was asked to assess how important each technique and design strategy was using the Likert scale from 1 to 5. As a result, the techniques which were not considered to be important were dismissed. The techniques recommended by the experts were reassessed in the following rounds. Moreover, each expert was required to contribute further techniques and design strategies, not covered in the questionnaire, based on their experience. The purpose of this round was to assess the value of existing techniques and design strategies, whilst adding new ones based on expert experience.

- **In the second round, (the Narrowing-Down round),** the questionnaire was updated in accordance with the new techniques and design strategies put forward by the experts in the previous brainstorming round. Based on expert assessment from the previous round, techniques and strategies which were considered unsuitable were removed. In this round, the experts re-assessed the design techniques and strategies while being able to see and assess those put forward by other experts in the previous round.
- **In the third round (Rating Round),** the aim was for the experts to carry out a final assessment of the techniques and strategies to reach a final consensus (Diamond et al., 2014, von der Gracht, 2012, Dalkey and Helmer, 1963). The latter was formed from the statistical results of the Interquartile Range (IQR) (Gnatzy et al., 2011) which is based on the Liker Scale (ranging from 1 to 5 units in this study). The IQR of each design technique and strategy should be

between 0 to 1 ($0 \leq IQR \leq 1$). The questionnaire in this round included the statistical information of experts' assessments from the Narrowing-Down round to help the experts form their final decisions and achieve the consensus among the experts (von der Gracht, 2012). The outcome of the consultation in this final round was an agreement shared between experts about an efficient low carbon domestic design framework for sustainable homes.

#### *3.3.3.3 Criteria for Selecting Expert Panels*

The type and number of expert on a panel is important in order to achieve the Delphi consultation objectives and reach the consensus. The expert panel size selected is common to other Delphi studies. Many previous studies recommend keeping the number of experts below 50, as the likelihood of error increases with the size of the panel. For a successful study using the Delphi Technique, it is essential that the right experts are selected (Okoli and Pawlowski, 2004, Alshehri et al.). It is important when inviting experts in the context of a Delphi consultation, that the final retained number falls within the recommended average common to panel size to avoid any risk of error in the subsequent study. In that respect, the size of the proposed panel is in line with guidance. According to Witkin (1995) a common size for Delphi expert panels is fewer than 50 members (Witkin, 1995). Conversely, Clayton (1997) suggests that panels comprising between 15 and 30 experts offer an acceptable number (Clayton, 1997). Moreover, other studies have reported that expert panels can range in size from 10 to 15 (Paliwoda, 1983), and between 10 and 18 (Okoli and Pawlowski, 2004). Consequently, in line with Witkin, 40 experts completed the consultation process in the present study over three consecutive rounds. The experts were invited to participate individually by e-mail. The surveymonkey (www.surveymonkey.com) tool was used to distribute the questionnaires and analyse the feedback. All the experts invited to participate in the study were provided with a confidentiality guarantee, which is crucial when implementing a Delphi consultation study.

Selection of a panel of experts was considered important to cover decision makers, academies and building professionals according to (Okoli and Pawlowski, 2004). Unquestionably, it is useful to include experts currently in Saudi Arabia who were educated in developed countries, to transfer their knowledge and include experts who works in Middle East with experience in Saudi Arabia or GCC countries. The academics involved in this study already have experience as building professionals and have received higher education abroad in developed countries. Thus, they were also able to share details of their life styles and experiences. The other two categories of experts (decision makers and building professionals) have enough experience in Saudi Arabia and Middle East in the industry, especially relating to regulations, availability of raw materials, challenges and barriers. Consequently, the three groups of experts involved in this study will give strong feedback on means for establishing a low carbon domestic design framework for sustainable homes.

The experience of each expert is different based on the sector they work in and their particular role. The experts involved in this study have a background in the construction industry with experience in sustainability, as summarized below:

***(a)*** ***Decision Makers:*** experts selected as decision makers work with the government in different ministries and have influence in decision-making, including engineers and architects who work at the Ministry of Municipality, the Ministry of Housing, the Green House Council and other related ministries and those involved directly with the construction industry. Using the Snowball Technique (Biernacki and Waldorf, 1981), these experts (decision makers) were asked to refer the study on to other experts. These experts can give feedback based on their experience in decision making, policies and regulations in the country and how the policies in the construction industry could change in terms of energy conservation and $CO_2$ emissions, changes which have already been achieved in some developed countries.

***(b)*** ***Academics:*** experts who work in an academic field are important to this study because they are likely to have different points of view and perspectives, in comparison to decision makers. From their research, these experts can suggest new concepts and design strategies based on new methods and techniques which are being used in some developed countries. These academics needed to have completed a PhD, be lecturing at universities and have sufficient experience of working in their field. Academics were selected from different schools in different universities across Saudi Arabia, such as, King Abdulaziz University, King Saud University, Al-Baha University, the University of Dammam, Umm-Alqura University and Al-Jouf University. The academics chosen were asked to refer the study to other academics whose expertise would be of value to the study.

(c) ***Construction Industry practitioners (Private Sectors):*** experts who work as contractors or engineering consultants can participate and give feedback based on their experience as consultants. Their experience focuses on how to link sustainable/low-energy buildings with the demand, of the market and the availability of construction materials. Many experts from different companies in the private sector were involved in the study such as engineering consultant agents, real estate developers and construction companies. Similarly to the academics, the experts in this field were required to refer the study on to others. All of these experts have a background in building energy and sustainability.

The anonymity of expert panels is an important principle in a Delphi study (De Vet et al., 2005, Paliwoda, 1983, Okoli and Pawlowski, 2004). One of the principle ethical concerns underpinning the preparation of a Delphi consultation is that the experts panel must be anonymous throughout the consultation process and afterward (De Vet et al., 2005, Paliwoda, 1983, Okoli and Pawlowski, 2004). Table 3.2 presents the composition of the expert panel

**Table 3.2 Composition Of The Expert Panel**

| Category | Organization | Number of Experts | Expert Description |
|---|---|---|---|
| Academics | Al Jouf University<br>University of Dammam<br>King Abdulaziz University<br>King Saud University<br>Umm Al-Qura University<br>Al-Baha University | 13 | Established academics (PhD holders) who research and in the fields of sustainability and building energy |
| Decision-makers | Jeddah Municipality<br>Riyadh Municipality<br>Al-Baha Municipality<br>Najran Municipality<br>Ministry of Housing<br>Ministry of Electricity<br>Green Building Council<br>Housing Department – Design and Management and Construction in other Ministries | 13 | Decision makers with experience in low energy buildings and sustainability. These experts have original qualifications in Civil engineering, Built Environment, and Architecture. They are responsible for granting planning consent in line with local regulations |
| Building Professionals | Ewaan Global Company for Construction in Jeddah<br>Zuhair Fayez & Partnerships Leading Engineering and Construction Company in Saudi Arabia<br>Five design solutions (Engineering Consultations) in Jeddah<br>Al-Meter Engineering Consultation Group<br>Marwan Ahmed Nazer Engineering Consultation and Construction Company<br>Other Engineering Consultants | 11 | Engineering Consultants and construction practitioners in building energy and sustainability |
| Regional and International | Faculty of Engineering in Shubra - Egypt<br>Faculty of Engineering - Jordan University of Science and Technology<br>Kier Construction company - UK and Dubai UAE | 3 (Two Academics and one building Professional) | Experts from international companies with experience in the Saudi Arabian Context and the field of sustainability |

### *3.3.3.4 Data Collection - Delphi Questionnaire Description*

The first round questionnaire was informed by existing literature and findings from recent related studies, e.g. (Shi and Chew, 2012, Evins, 2013, Hamelin and Zmeureanu, 2014, Medio, 2013, Shetty et al., 2013, Valentín et al., 2013, León et al., 2012, Bustamante et al., 2014, Lai and Wang, 2011). As the first round is a brainstorming round, the questionnaire was designed to give the respondents (experts) the opportunity to add more techniques and strategies for the Saudi Arabian context not already covered by the questionnaire.

In this second round, each expert assessed the added techniques and strategies by the other experts and decided which techniques and strategies were not suitable for the climate and culture of Saudi Arabia. In this round the aim was to (a) re-assess the techniques from the first round and (b) assess the added techniques and strategies by the experts.

The final consultation round (final Rating Round) aimed at reaching a consensus about delivering low energy homes in Saudi Arabia.

The questionnaire for each round was divided into four main categories: architectural design techniques and strategies, house envelope technique and strategies, on-site renewable energy techniques and strategies, and socio-cultural issues.

- ***Architectural Design Techniques and Strategies:*** This category includes techniques and strategies that help the designers, architects and civil engineers design low energy buildings. These techniques and strategies are related to building design, building shape, shading devices, and HVAC systems.
- ***Building Fabric Design, Techniques and Strategies:*** this category in the questionnaire includes many different low carbon envelop design techniques and strategies. These strategies are related to building envelope, external walls design, roof design, floor design and external glazing.
- ***On-site Renewable Energy, Techniques and Strategies*** **and socio-cultural issues*:*** this category in the questionnaire includes many different strategies of using renewable energy techniques such as PV and some designs related to the socio-cultural issues. Experts had to assess each strategy and technique individually and add further strategies that are useful and efficient for Saudi Arabian vernacular architecture.

#### *3.3.3.5 Questionnaire Distribution*

The technique used to distribute the questionnaire to the experts in Saudi Arabia was the Snowball Sampling Technique (Biernacki and Waldorf, 1981), also referred to as chain-referral or link-tracing. In this approach the first set of participants are called seeds, who are asked to identify acquaintances (Illenberger and Flötteröd, 2012). The acquaintances they report are then asked to take part in a survey and also declare their own acquaintances. The ego-centric method is restricted to first degree associations, whereas as Snowball Sampling caters for an intricate grid (Illenberger and Flötteröd, 2012). In order to distribute the questionnaire to the experts in Saudi Arabia, the survey distribution was hosted on Monkeysurvey (www.surveymonkey.com). This tool can create the questionnaire in the form of an online link which can then be distributed in many different ways using the Snowball Technique. The responses can be monitored, viewed and then analyzed.

### 3.3.4 Stage Four: Establishing Domestic Low Energy Consumption Reference Levels For Saudi Arabia And The Wider Middle Eastern Region

The issue of managing and controlling the energy consumption in domestic buildings has been a topic of increasing relevance and prominence in many developed countries. This has led to the creation and use of energy consumption definition systems (in kWh/m²), which have been designed on the basis of their local needs and environment. The final research questions in this study seek to identify the level of low energy consumption that can be achieved in Saudi Arabia, thereby suggesting a definition system for low energy consumption in the specific Saudi Arabian context (in kWh/m²). This system should be supported by a prediction of the economic and environmental benefits that could potentially be reached by implementing these kinds of low energy building strategies.

This stage utilises the framework established during the previous stage. The framework was used to design multiple low energy homes for the Saudi Arabian climate and cultural requirements in order to establish a low energy consumption definition system and validate the design of the established framework. Simulation software tools were required to validate the efficiency of the proposed design of low energy homes. The design of different homes on the basis of the established framework design strategies taking into account the cultural requirements was achieved through adherence to a clear, quantitative approach:

- Objective one: Designing three different homes in accordance with the established low carbon design framework, taking into account the cultural requirements.
- Objective two: Validate each designed home by employing IES-VE software tool to identify predicted energy consumption levels, which can then be extrapolated to Saudi Arabia as a whole.
- Objective three: Establish a low energy consumption definition system in kWh/m² for the Saudi Arabian climate and cultural requirements. This system should be benchmarked against established international low energy consumption definition systems that already use kWh/m².

- Objective four: Estimate the economic and environmental benefits that can be achieved through the official use of the established low energy consumption definition in Saudi Arabia

This study is informed by established low carbon domestic design standards and frameworks. The proposed interventions will focus on: (a) architectural design (massing and space layout), (b) house envelope (fabric), and (c) on-site renewable energy strategies. Moreover, three proposed house prototypes will be assessed with respect to their predicted energy performance.

One of the challenges of this research is creating design interventions acceptable by the general public in Saudi Arabia. Socio-cultural and religious practices dictate particular spatial arrangements such as separate guest rooms (reception rooms) for males and females (Aldossary et al., 2014a, Aldossary et al., 2014b). Moreover, Saudi families are quite large (often with complex family structures) requiring large spaces to meet their needs. Another challenge is how to persuade people to prioritize sustainability as a driving criterion for their home design? Evidence suggests that Saudis prefer to live in large houses to accommodate their large families and / or to display them as symbols of their social status (Opoku and Abdul-Muhmin, 2010).

Cultural requirements and challenges are one of the important principles to consider when designing a home. Housing is designed according to client requirements, site conditions and client budget. To meet the research goals, it is important to add an environmental requirement alongside the design principles. On the other hand, some people accept changes to socio-cultural requirements to attain sustainable low energy homes and meet religious requirements.

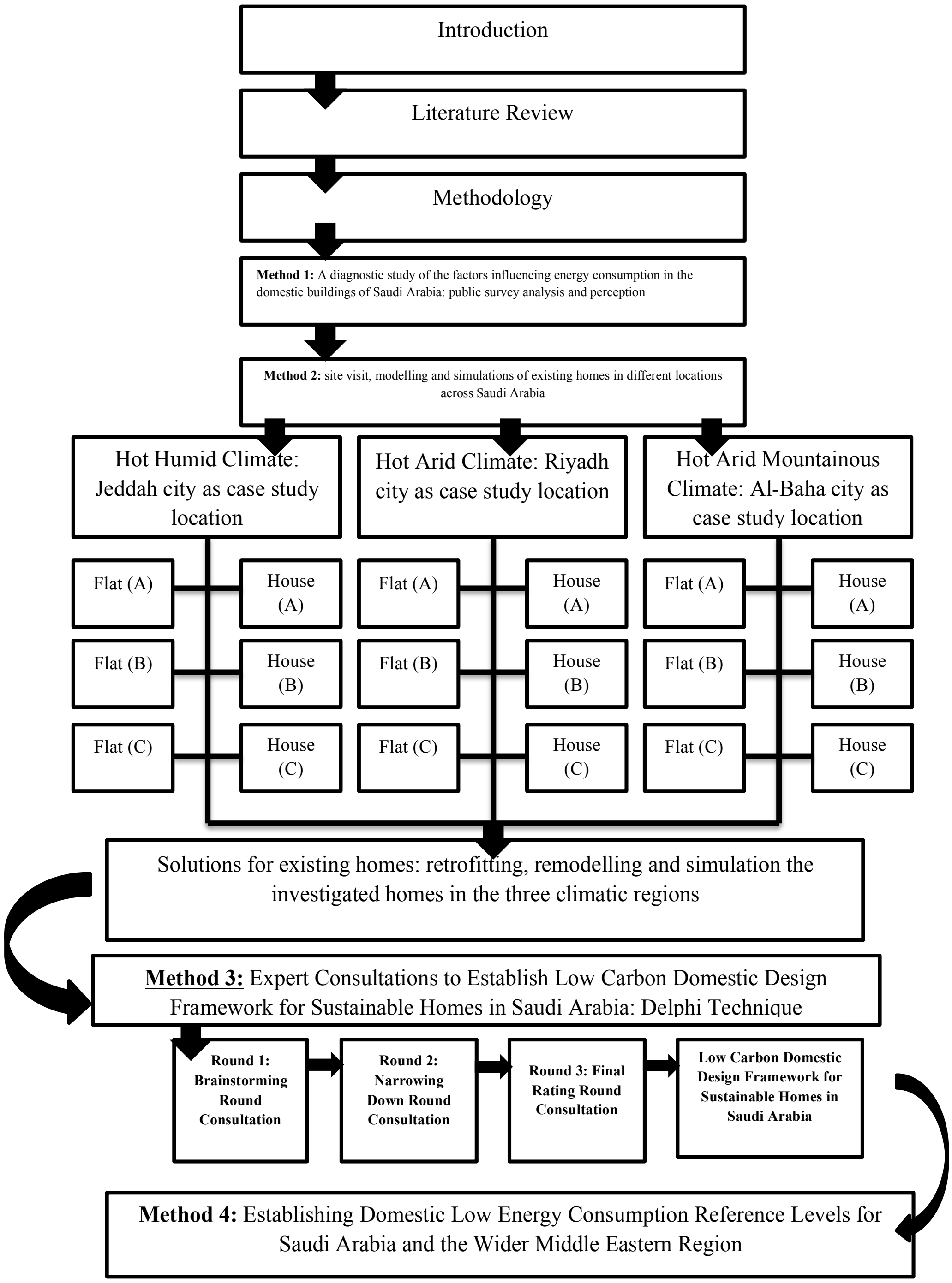
First, it is necessary to design a single option that offers a sustainable, low energy home, retaining the size and space expected in a typical house in Saudi Arabia. This option will meet the requirements of people with a large family. Moreover, this option will meet the requirements of people who do not want to deviate from socio-cultural norms, while keeping energy consumption as low as possible. On the other hand, it was decide to offer two alternative design options of a smaller size with different design criteria and styles to show better energy performance and lower energy consumption. These two options will meet people's requirements, if they prioritise lower energy consumption in their future homes.

Three prototype houses are proposed reflecting current socio-cultural requirements. These prototypes are of decreasing sizes, and of varying space layouts, fabric designs and renewable energy integration:

- **House Prototype1:** This design reflects current Saudi large houses and is as such suitable for a large family. It is designed to optimize energy efficiency by enhancing the envelope (including openings), using shading devices where appropriate, and integrating on-site renewable solutions.
- **House Prototype 2:** This prototype aims at families with fewer occupants and willing to reduce their energy footprint. It is medium-sized compared with typical Saudi houses. Similar energy efficient interventions are applied as to prototype 1.
- **House Prototype 3:** This conveys the most energy efficient design taking into account the Saudi socio-cultural and environmental conditions, with lesser living space.

This research follows on from related studies that have successfully utilised simulation tools, including IES-VE, to establish an energy profile of a given house / building (Al-Tamimi and Fadzil, 2011). A Building Information Model (BIM) is developed for each house prototype. As indicated earlier, all designs focus on: (a) massing and space layout, (b) envelope, including construction materials used for external walls, roof, floor and external glazing, (c) on-site renewable energy strategies, and (d) user profiling (of the occupants), informed by earlier studies (Aldossary et al., 2014a, Aldossary et al., 2014b). The main outputs from the energy simulation are: (a) estimates of annual energy consumption in kWh and in kWh/m$^2$ and (b) $CO_2$ emission rates. Also, energy consumption is calculated hourly throughout the year, including each season. A profiling of energy use is also provided, including air conditioning, lighting, domestic hot water (DHW), and white goods.

## 3.4 Thesis Flowchart



## 3.5 Summary

The four approaches of the designed methodology are intended to ensure that the main aim can be reached, through the identification of barriers and ensuring that related objectives are met. As indicated in the flowchart above, questions related to each of the four stages of the research are addressed through corresponding methods, which compose the methodology of this thesis. The mixed method approach has been used in this research. This combined methods approach has involved: (a) data collection and analysis through public survey, which sought to identify key architectural design problems, public perception and cultural barriers preventing the design and establishment of sustainable homes in Saudi Arabia. (b) An additional quantitative approach to determine inherent building design weaknesses, as they pertain to its form, fabric and on-site renewable energy uses of the building. This information was not available through public survey analysis and therefore required empirical data collection, through site visits and modelling, supplemented by the use of software simulation tools to investigate the energy consumption patterns in different existing occupied homes across Saudi Arabia. (c) A qualitative approach to develop a contemporary, targeted low carbon design framework. This stage relied upon the use of the Delphi technique to integrate the opinions of experts in three different rounds, with the aim of establishing a framework for the specific design of low energy homes in Saudi Arabia. (d) Designing and validating low energy homes for use within the Saudi Arabian climate, context and cultural requirements, enabling the study to offer suggestions of how to create a low energy consumption definition system in $kWh/m^2$. These four main approaches enabled the research questions and objectives to be met. The next chapters will present the findings and discussions of each stage individually.

# Chapter 4 : A diagnostic study of the factors that influence energy consumption in domestic buildings in Saudi Arabia: public survey analysis and perception

**This chapter has been published in *Habitat international journal***

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http://dx.doi.org/10.1016/j.habitatint.2015.01.002

## 4.1 Introduction

This chapter focuses on public perception of sustainable homes in a developing economy, namely Saudi Arabia, known for its high energy consumption and $CO_2$ emission rates. The research explores (i) public perception and knowledge of sustainable and/or low energy homes, (ii) domestic stock typology (including architectural style), (iii) energy consumption patterns and levels of satisfaction of energy (i.e. HVAC) systems, (iv) cultural barriers that prevent the delivery of low energy homes, and (v) people's acceptance of energy retrofitting and / or sustainable homes. For this purpose, a comprehensive survey (n= 622) was conducted across the country. The findings reveal limited public awareness of sustainable and low carbon homes, as well as important socio-cultural barriers to the delivery of sustainable homes and large scale retrofitting of existing domestic stock.

In order to address the problem of energy saving in the domestic sector in Saudi Arabia, it is important to examine factors causing high energy consumption, including public perceptions and the socio-technical barriers that prevent development of sustainable homes and energy retrofitting programs. A large scale survey was conducted, using a questionnaire distributed to members of the public with different ages, levels of education, and cities of residence in Saudi Arabia as it was described in the methodology chapter 3 section 3.3.1 pp. 65-67. The questionnaire focused on the existing building stock, the behavior of occupants, and their perception of what constitutes sustainable dwellings. Following this introduction, this chapter is structured into four main sections: results and analysis, discussion, benefits and suggestions for large scale implementation, and finally summary.

## 4.2 Results And Analysis

The use of the snowball technique through SurveyMonkey proved satisfactory; the questionnaire reached 622 participants, 502 of whom (80.7%) completed and submitted the questionnaire. Table 4.1 presents the demographics of the completed respondents across Saudi Arabia regions in the basis of the ministry of electricity energy supply.

**Table 4.1 Demographics Of The Respondents**

| Characteristic<br>Age | Percentage | Characteristic<br>Education Level | Percentage | Characteristic<br>Gender | Percentage |
|---|---|---|---|---|---|
| From 18 - 34 | 67.58% | High school | 14.8% | Male | 83.79% |
| From 35- 49 | 28.09% | Diploma | 9.3% | | |
| From 50- 64 | 3.21% | A bachelor's Degree | 47.4% | Female | 15.25% |
| More than 64 | 1.12% | Master's Degree | 20.7% | | |
| | | Ph.D | 7.7% | Rather not to say | 0.96% |

| Characteristic<br>Location of Respondents | Percentage |
|---|---|
| Central Region | 36.82% |
| Northern Region | 12.86% |
| Southern Region | 11.25% |
| Eastern Region | 10.93% |
| Western Region | 28.14% |

The survey results are presented in this section according to the identified categories: (a) public perceptions and current issues; (b) preparedness of the public to retrofit their homes; (c) ability of the public to have sustainable homes in the future; and (d) socio-cultural barriers. The sub-sections below analyze and discuss each identified category.

### 4.2.1 Public Perception And Current Problems

Through an in-depth analysis of public perceptions and review of their energy consumption behaviors, a number of factors emerged providing an initial explanation of high energy consumption patterns in the residential sector in Saudi Arabia, as elaborated below.

#### *4.2.1.1 Building massing and space layout*

The questionnaire involved questions to identify, assess and determine the factors that cause high energy consumption in domestic buildings in Saudi Arabia. The results highlight a number of factors related to building size, number of rooms, as well as the number of household members in each property. Firstly, it is important to note that the majority of respondents live in one or two storey houses (52.84%), with just under half living in flats (47.61%). See Figure 4.1 for more details.

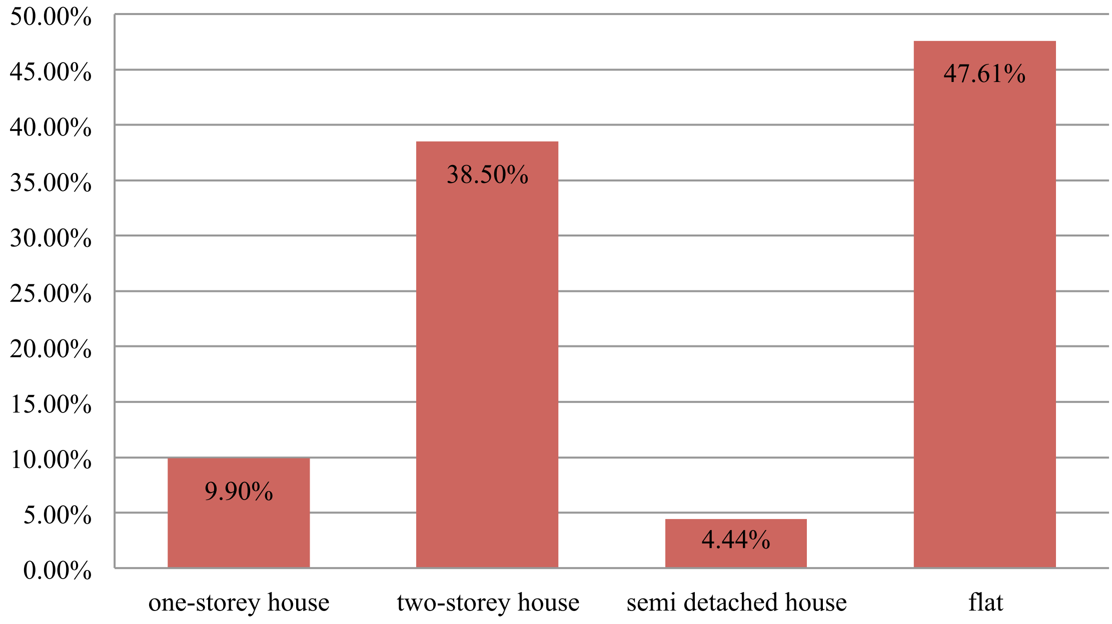



**Figure 4.1 Types Of Respondents' Dwellings**

This corroborates official sources which state that 41.1% of properties are flats while 54.8% of properties are houses, with 4.2% in other categories. On the other hand, about half the respondents live in properties with areas of 300 up to 1000m² (Figure 4.2).

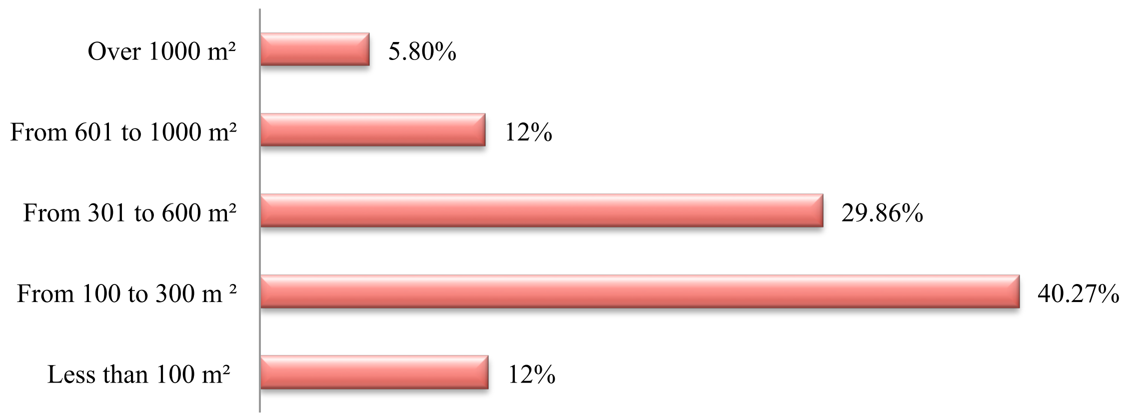



**Figure 4.2 Size Of Respondents' Dwellings**

Moreover, many of these respondents have extra rooms; e.g. many properties have over 5 bedrooms and over 5 toilets (Figure 4.3). This figure indicates the amount of energy that will be consumed to operate the additional spaces in the home.

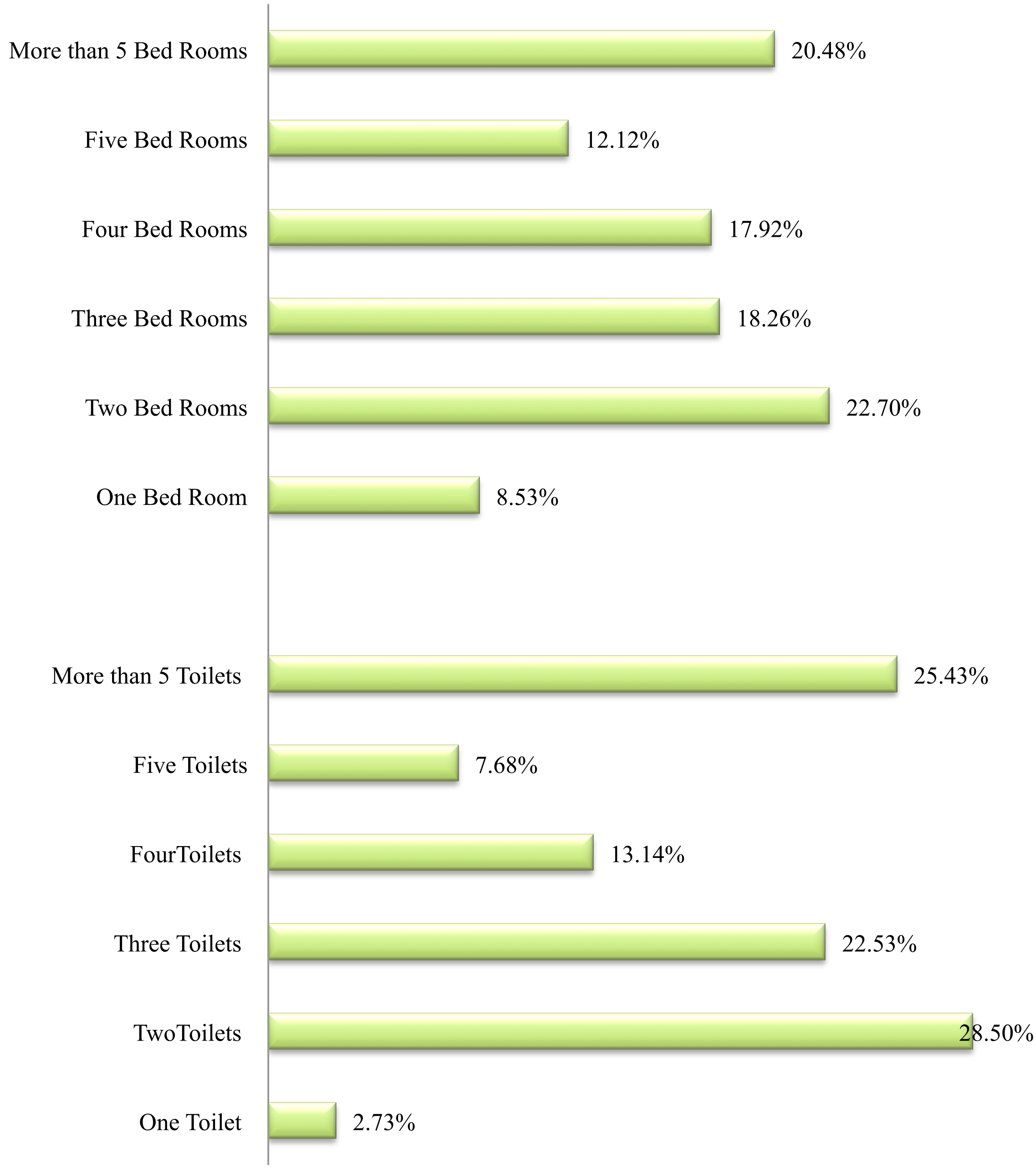



**Figure 4.3 Number Of Bedrooms And Toilets In Respondents' Dwellings**

The number of rooms in a majority of properties is relatively high and some rooms are not used continually. For example, about 77% of respondents have two separate guest rooms, one for males and the other for females (Figure 4.4). Some of these have two rooms for male guests and another two rooms for female guests.

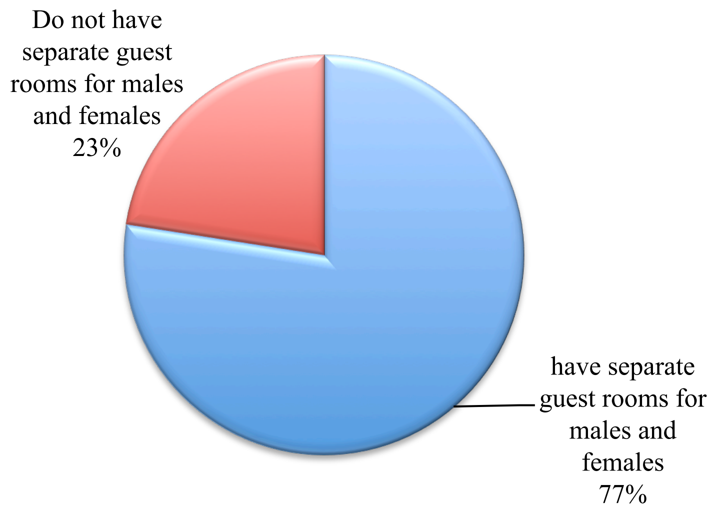



**Figure 4.4 Separate Guest Reception Rooms In Respondents' Dwellings**

These additional spaces are heated / cooled and represent a source of energy wastage. In addition, many properties have extra unnecessary areas also heated / cooled and lit during night. Conversely, families tend to be large with an average of 7 members (Figure 4.5). This will be further elaborated in the discussion section.

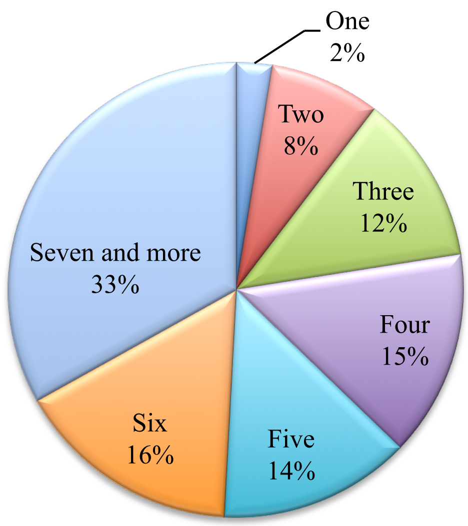



**Figure 4.5 Number Of Occupants In The Property**

A positive sign is that the majority of respondents are well informed about the cost of electricity. About 84% of respondents knew the amount of their monthly electricity bill which, however, does not seem to raise any concern as electricity prices are subsidized (Alyousef and Stevens, 2011).

#### *4.2.1.2 Cooling and heating use*

The survey suggests that cooling loads are relatively high and represent the major source of energy consumption, given that Saudi Arabia has a very hot and aggressive environment that requires mechanical ventilation and air conditioning. Moreover, air conditioning is used as the main cooling system, without any reliance on natural ventilation, as illustrated in Figure 4.6. The figure presents the techniques used for cooling. It is worth noting that this part of the questionnaire is designed to allow for more than one answer, as in some parts of Saudi Arabia, such as the high mountain region in the south, people can use natural ventilation in summer during the night.

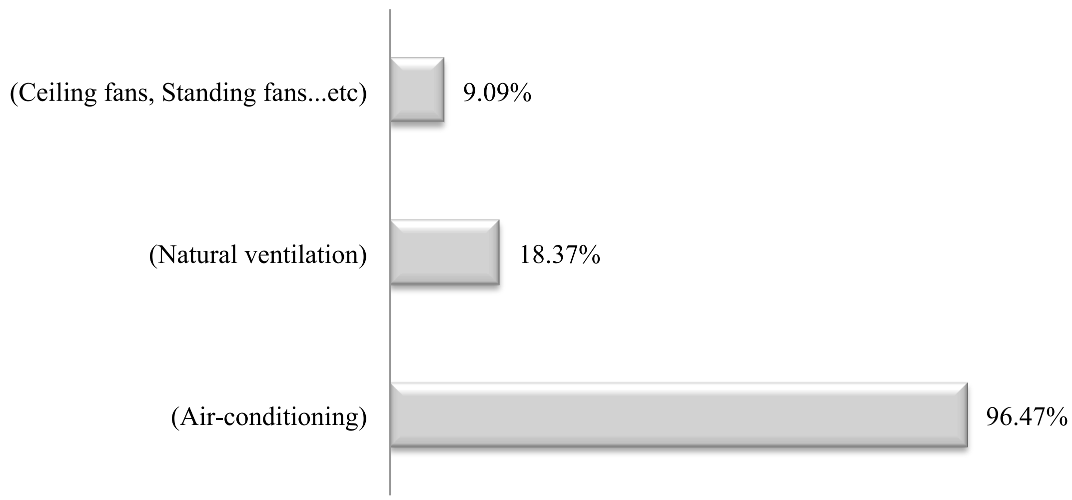



**Figure 4.6 Cooling Systems Used In The Properties**

Conversely, about 35% of respondents report not necessitating a heating system as the weather in Saudi Arabia is hot in summer and usually warm in winter.  The cold period tends also to be short in some cities, e.g. Table 4.2 presents the climate conditions in Jeddah city.

**Table 4.2 Jeddah City Climate Data (CDOS, 2008)**

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Max Temperature** | 32 | 35 | 39 | 42 | 42 | 48 | 45 | 41.5 | 42 | 43 | 38 | 36.5 |
| **Min Temperature** | 13 | 15.4 | 18 | 19 | 20 | 23.4 | 24.8 | 25 | 23.8 | 20 | 20 | 17 |
| **Relative humidity** | 59 | 56 | 60 | 58 | 56 | 58 | 49 | 52 | 66 | 61 | 65 | 51 |

Following the previous two figures, Figure 4.7 illustrates the average period during which homes are occupied each day.

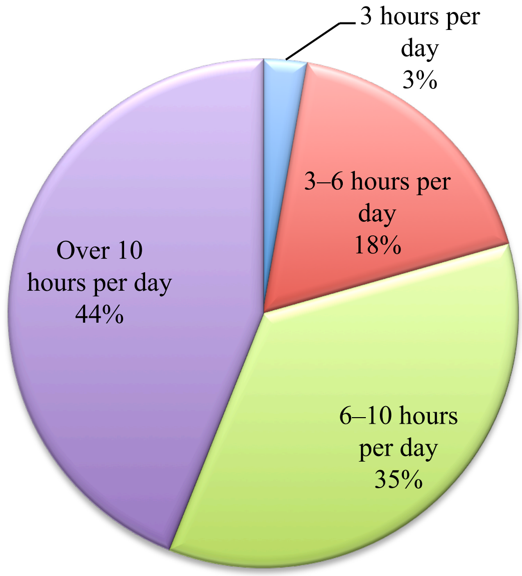



**Figure 4.7 Average Period Per Day During Which Homes Are Occupied**

Figure 4.7 shows that the home is occupied for long periods in the day, with the air conditioning used in all or most of the rooms, as reported in Figure 4.6. Moreover, homes are occupied over 18 hours a day on average with the air conditioning in operation during hot seasons. To support this finding, one question was designed to assess the period of operation of the air conditioning. Figure 4.8 illustrates the period during which air conditioning is used in the home: over 73% of respondents use air conditioning between 10 to 24 hours a day. This reflects the amount of kWh being used to operate the air conditioning during the summer period.

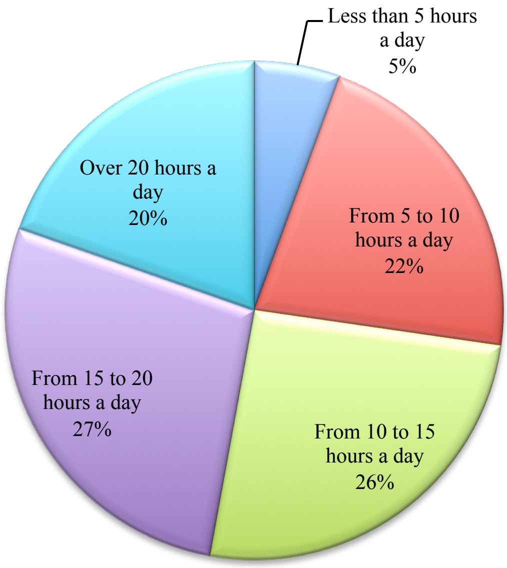



**Figure 4.8 Average Period Of Using Air Conditioning In The Dwellings**

The negative side of the picture is that occupants are not always content to use natural ventilation and/or fans in hot seasons. The majority of respondent (88%) are not satisfied with these methods. This poses the challenge to regulate the use of air conditioning so as to achieve the lowest possible energy consumption.

#### *4.2.1.3 Architectural design factors*

Many architectural factors resulting in high energy consumption were revealed by the survey. Figure 4.9 presents these factors in detail. Some questions are repeated to the respondents from another perspective to confirm their answers.

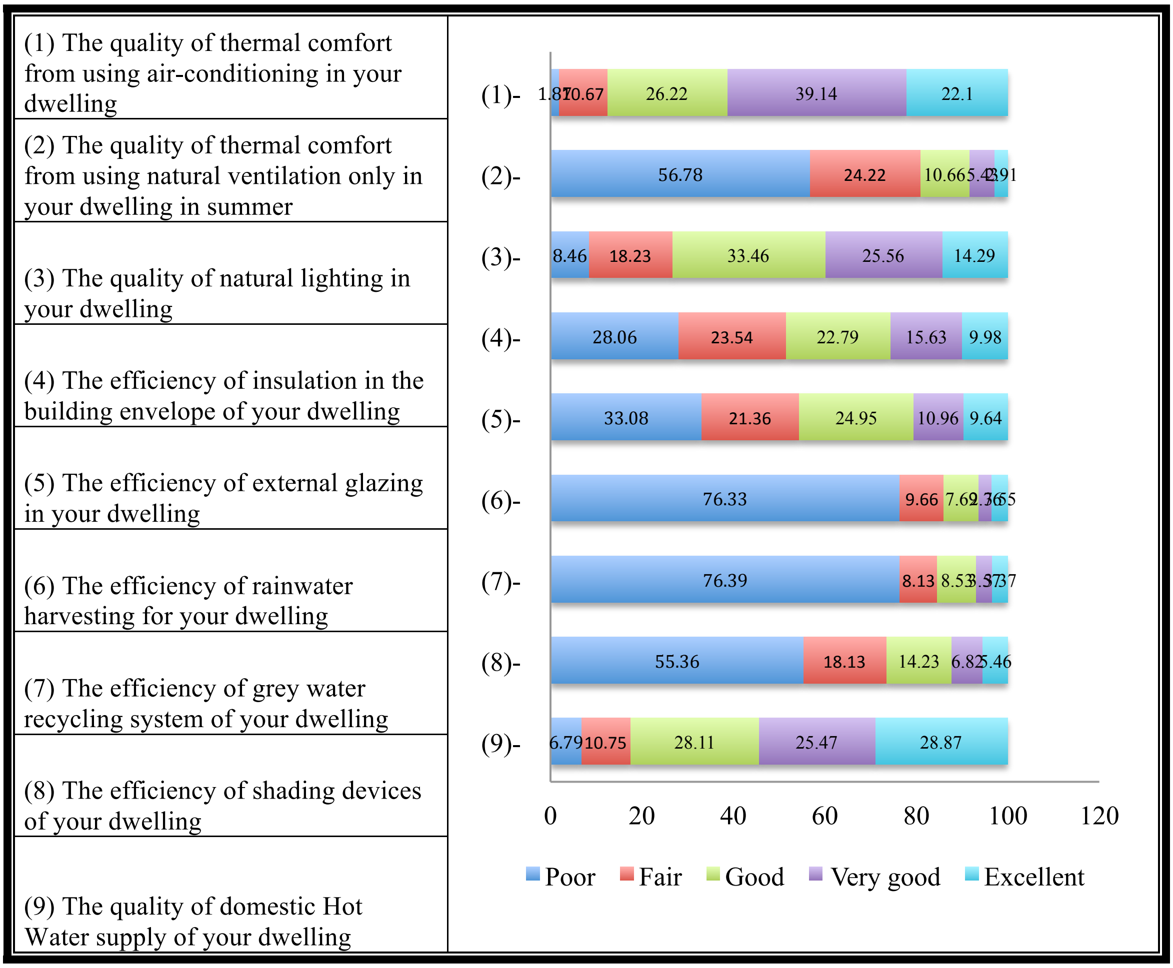



**Figure 4.9 Public Evaluation Of Architectural Design Factors Causing High Energy Consumption**

The respondents confirmed that they were satisfied with the internal comfort of the environment provided by air conditioning, while the majority was not satisfied with the quality of natural ventilation. Insulation is an important factor that must be taken into account (about 51.6% respondents assessed the insulation as between poor and fair). In addition, the efficiency of shading devices is poor, as seen in the figure above. On the basis of the factors mentioned, there is a great opportunity to reduce energy consumption by developing more efficiently designed insulation and shading devices. Lighting is another source of energy use in the home. About 33.4% of respondents stated that natural lighting is good but about 26.7% were not fully satisfied.

Finally, water management is an important factor in terms of energy savings. Domestic hot water is provided by boilers, which satisfies the majority of respondents. The boilers' energy usage to provide Domestic Hot Water (DHW) can reach up to 20% of the whole building energy consumption, as stated in (Aldossary et al., 2014a), while solar energy usage is absent. The negative aspect lies in the poor quality systems of grey water recycling and rainwater harvesting.

### 4.2.2 Willingness Of The Public To Have Sustainable Homes In Future

The survey results reflect a positive image regarding people's willingness to have sustainable homes in future as well as to retrofit their homes to save energy. Firstly, it is important to mention that over half the respondents claim that they are well informed about sustainable homes with less energy demand (Figure 4.10), but about 42% lack awareness. The respondents who know about sustainable homes were informed through internet websites, media, news, television programs, background experience, friends, and advertisements, while some respondents specialize in subjects related to sustainability.

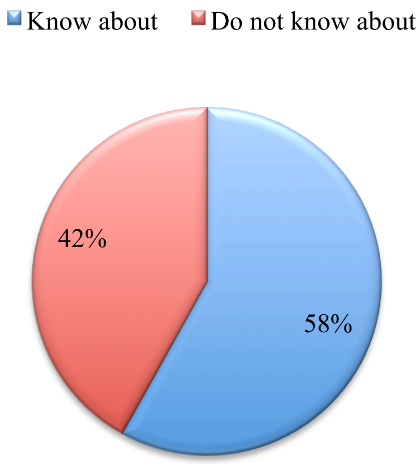



**Figure 4.10 Experience Of The Public Regarding Sustainable/Low Energy Or Green Buildings**

Another positive sign is that the majority of respondents generally agreed to promote sustainable buildings in the Kingdom of Saudi Arabia in the future. Figure 4.11 summarizes the motivation behind this drive. These figures are an encouraging sign for Saudi authorities to face the challenge of designing sustainable homes that meet the occupants' needs and respect their culture.

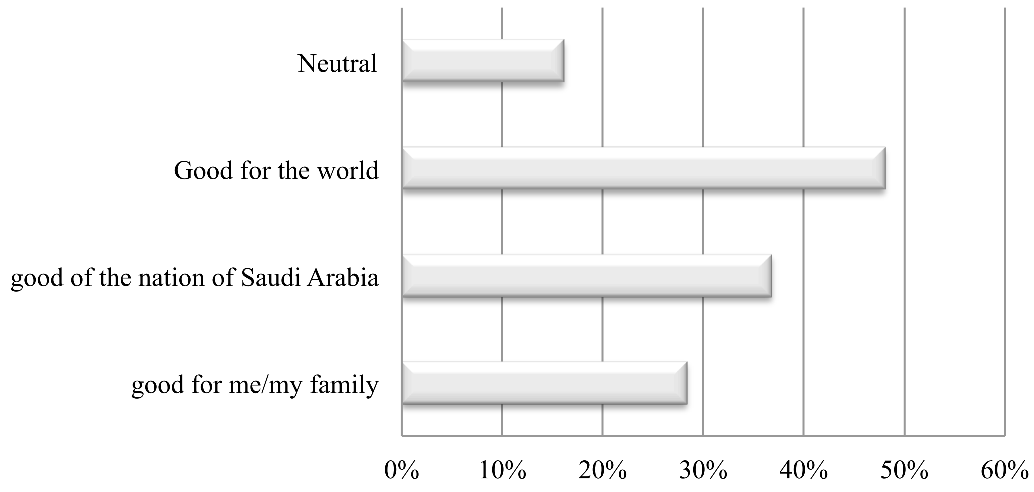
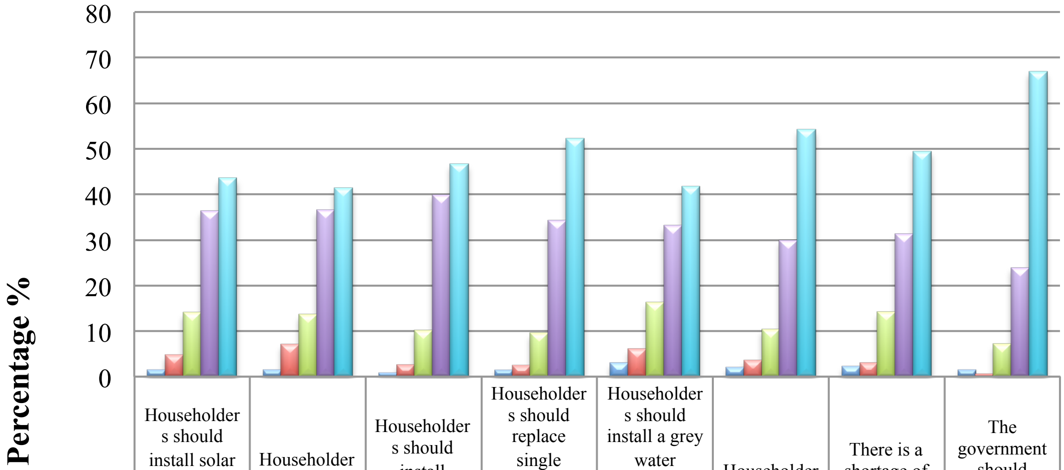



**Figure 4.11 Rationale Behind The Promotion Of Sustainable Homes**

A fundamental objective of the survey was to arrive at an accurate and detailed assessment of people's willingness to adopt sustainability measures. As a result, multiple questions were incorporated into the questionnaire testing people's willingness`as well as intention to adopt proven, energy saving techniques in their homes. According to the survey, as illustrated in Figure 4.12, over 36.4% of respondents agree and 43.5% of respondents strongly agree that house owners should install PV systems in their homes to generate electricity. Moreover, Figure 4.12 illustrates several techniques and the level of willingness to use them in order to promote sustainable homes. For example, the majority of respondents agreed that the landlord of a property must use a solar heating storage tank to heat domestic hot water from a solar radiation source rather than from electricity generated by burning fossil fuel. This technique will reduce the energy demand produced in heating domestic water, as corroborated by related studies (Aldossary et al., 2014a, Aldossary et al., 2014b). Additionally, the building should be designed in a way that exploits shading products. Over 85% of respondents agreed/ strongly agreed that landlords of properties should use shading products around external windows to reduce energy cooling demand. They should further replace the poor single glazed windows with efficient double or triple glazing and install a grey water recycling system, as reported in Figure 4.12.

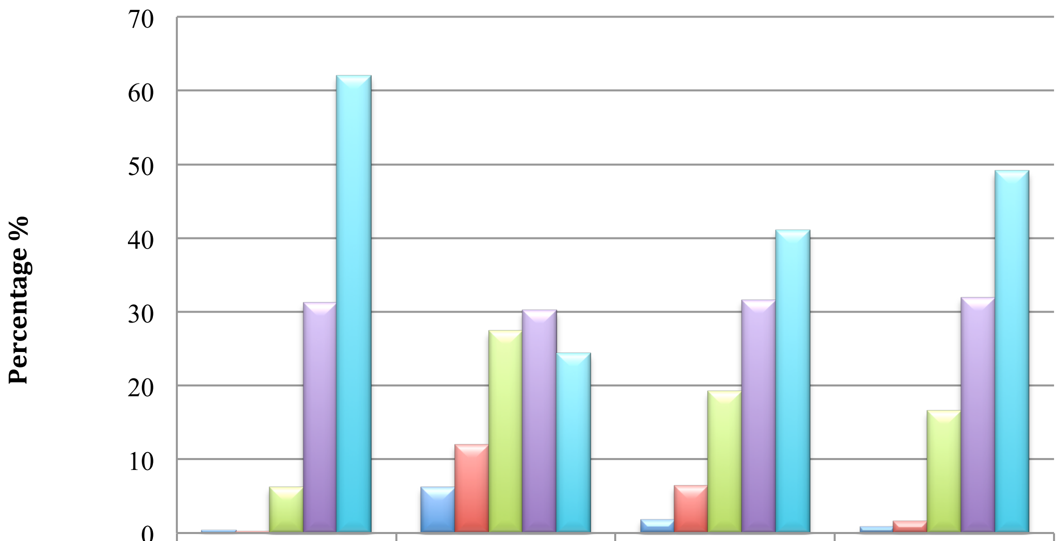



| | Householders should install solar electricity generation systems, e.g PV, to reduce reliance on national electricity grid | Householders should use solar radiations for water heating to save energy | Householders should install shading devices around windows to reduce solar gains in hot seasons | Householders should replace single glazing with double or triple glazing to improve the thermal performance of their homes | Householders should install a grey water recycling system for irrigation purposes, to create more vegetation around their dwelling | Householders lack awareness of low carbon energy buildings | There is a shortage of sustainable products such as PV on the Saudi market | The government should regulate the energy market and promote sustainable buildings |
|---|---|---|---|---|---|---|---|---|
| Strongly disagree | 1.38 | 1.38 | 0.79 | 1.58 | 2.99 | 1.99 | 2.19 | 1.39 |
| Disagree | 4.72 | 7.1 | 2.58 | 2.38 | 5.98 | 3.59 | 2.99 | 0.6 |
| Neutral | 13.98 | 13.61 | 10.12 | 9.5 | 16.33 | 10.36 | 14.14 | 7.17 |
| Agree | 36.42 | 36.49 | 39.88 | 34.26 | 33.07 | 29.88 | 31.27 | 23.9 |
| Strongly agree | 43.5 | 41.42 | 46.63 | 52.28 | 41.63 | 54.18 | 49.4 | 66.93 |

**Figure 4.12 Public Views On Procedures To Follow In Order To Establish Sustainable Homes In Saudi Arabia**

Finally, over 84% of respondents strongly agreed (54.18%) or agreed (29.88%) that the lack of householders' awareness about sustainable or low carbon buildings, would result in substantial increase of energy demand. However, it is worth noting that there is a shortage of sustainable products, such as PV, in the Saudi market, as reported in Figure 4.12. The governmental sector should regulate the market and promote the wide availability of necessary low carbon and renewable products.

In terms of future plans of residential buildings, many questions in the survey were focused on ascertaining the public's views on the design of future homes with a focus on energy saving. According to the survey, as shown in Figure 4.13, over 90% of respondents strongly agreed (62.00%), or agreed (31.20%), that future dwellings in Saudi Arabia must be designed to take into account the need to save energy and reduce $CO_2$ emissions.



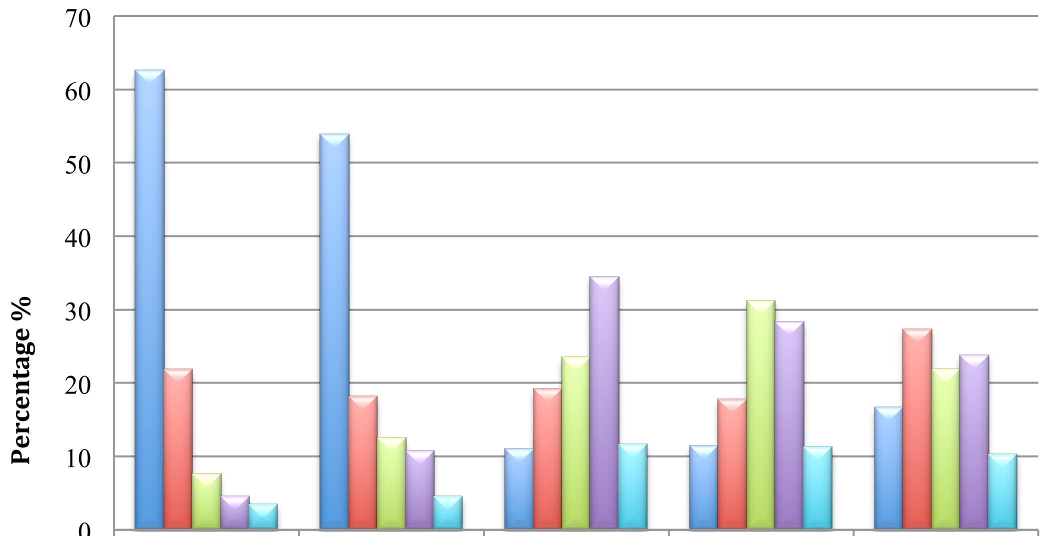

| | Future dwellings in Saudi Arabia must be designed to save energy consumption and CO2 emissions | The sizes of future dwellings in Saudi Arabia should be reduced to fit the household members | Future dwellings must be designed according to sustainable criteria established as compulsory by the government | The government should take serious steps to introduce rules to adopt sustainable buildings in Saudi Arabia |
|---|---|---|---|---|
| Strongly disagree | 0.4 | 6.19 | 1.8 | 0.8 |
| Disagree | 0.2 | 11.98 | 6.4 | 1.6 |
| Neutral | 6.2 | 27.35 | 19.2 | 16.57 |
| Agree | 31.2 | 30.14 | 31.6 | 31.94 |
| Strongly agree | 62 | 24.35 | 41 | 49.1 |

**Figure 4.13 Views Of The Public On Having Sustainable Homes In Future In Saudi Arabia**

This percentage highlights the overwhelming willingness of the public to accept sustainable buildings, although probably some aspects will experience slow acceptance / adoption, especially those related to the size of the houses or reduction in the number of rooms. It is worth noting that 54.5% of respondents strongly agreed or agreed on reducing houses overall area, but this percentage is relatively low compared with the acceptance other suggestions, such as the installation of PV. On the other hand, around 81% of respondents strongly agreed or agreed that the governmental sector, such as the Ministry of Electricity and the municipalities, should take serious steps to regulate the building sector in Saudi Arabia in term of energy conservation.

### 4.2.3 Social And Cultural Barriers

A number of cultural barriers emerged from the analysis of the survey that hinder the promotion of sustainable homes in Saudi Arabia (Figure 4.14). Some of these barriers are rooted in tradition and religion (e.g no mixed genders in a room), resulting in the design / allocation of additional rooms and areas requiring cooling, heating and lighting.




| | Public willingness to have one guest room for both genders | Public willingness to have one facility room for both genders | Public willingness to reduce bedrooms size | Public willingness to have sloped, as opposed to exclusively flat, roofs | Public willingness to have smaller and fitter for purpose houses |
|---|---|---|---|---|---|
| Strongly disagree | 62.55 | 53.89 | 11.07 | 11.47 | 16.73 |
| Disagree | 21.86 | 18.22 | 19.27 | 17.78 | 27.38 |
| Neutral | 7.6 | 12.52 | 23.47 | 31.17 | 21.86 |
| Agree | 4.56 | 10.82 | 34.54 | 28.3 | 23.76 |
| Strongly agree | 3.42 | 4.55 | 11.64 | 11.28 | 10.27 |

**Figure 4.14 Public Views On Cultural Barriers Hindering The Promotion Of Sustainable Homes In Saudi Arabia**

## 4.3 Discussion

As preseted earlier, there is some factors that hinder sustainable buildings in Saudi Arabia. This can be attributed to (a) the low price of electricity (Alyousef and Stevens, 2011) and (b) the free attribution of land and easy access to mortgages, reducing drastically the cost of dwellings (Sidawi and Meeran, 2011). However, public awareness can play a significant role in educating citizens as to the importance of reducing energy demand and relying on clean energy generation sources. It can promote sustainable and environmental friendly design interventions. Also, governmental authorities should revise their subsidized energy schemes and promote low carbon homes supported by sustainable lifestyles. One suggestion would be to estimate the energy demand for each property, based on the number of occupants and other relevant factors, and using this estimate to allocate a fixed energy price. Any usage exceeding the estimated demand would have to be paid full price. This would encourage occupants to adopt energy saving solutions while positively changing their lifestyles.

According to the Saudi regulations, clients can choose their engineering consultant to design their home. Then the client applies to the Ministry of Municipality to issue a construction permit based on some planning criteria, such as (a) the built area must not exceed 60% of the site area, and (b) the distance between the building and neighbouring boundary line must not be less than 2m. Additional requirements should be instituted to address sustainability requirements, including energy saving design principles. Relevant authorities should oversee the delivery of the planning consent in line with the above principles. Finally, the Saudi market for sustainable products such as PV and solar storage tanks should be widely available, possibly subsidized, and positively regulated. These products would also encourage home owners to retrofit their existing homes so as to become more energy efficient.

A number of factors that engender high energy demand have been identified. These factors are discussed from the following perspectives: (i) energy demand, (ii) socio-cultural blockers, (iii) engagement with low carbon interventions, and (v) wide acceptance of a sustainable home regulatory environment. Thus, the discussion will be divided into the following four main categories, mirroring the formulated research questions:

- Factors increasing energy demand.
- Socio-cultural blockers that hinder sustainable homes.
- Engagement with low carbon interventions.
- Environmental assessment and regulatory compliance environment

### 4.3.1 Factors Increasing Energy Demand

Many recent studies have identified factors that contribute to high energy demand in domestic buildings. Energy consumption, levels of cooling systems, heating and domestic hot water (DHW) systems and lighting are highly dependent on factors such as building envelope design (Zhu et al., 2013), the nature of the housing unit, the system of energy control, occupants' behavior and local climatic conditions (Pérez-Lombard et al., 2008, Shimoda et al., 2007, Swan and Ugursal, 2009, Hartkopf et al., 2012). Moreover, energy consumption in domestic buildings differs according to housing types (Brounen et al., 2012).

Many of these factors leading to high energy consumption in domestic buildings have been identified in Saudi Arabia. As illustrated in the analysis section, some of them can be addressed in existing homes, but others cannot be altered retrospectively and need to be taken into account at the design/construction stage. These factors relate to the constructed size of the property, the cooling and/or heating system used in the property, and public awareness in terms of energy conservation. These factors are discussed below:

- ***Constructed area of the property:*** According to Hirst, Goeltz et al (1982), floor area has a disproportionately negative effect on energy consumption. An increase in floor area will result not just in a corresponding increase in energy consumption per square meter, but in one exceeding that level (Hirst et al., 1982). Moreover, the number of occupants in a property (household size) is an important factor in determining the energy consumption of domestic buildings (Brounen et al., 2012, Kaza, 2010). Amongst the various social-economic determinants of energy consumption in domestic buildings, the number of occupants (size of household) has the highest impact on energy use (Kelly, 2011).

  Firstly, it is important to emphasise the relevance of the subsidising of the energy and petroleum industry in Saudi Arabia. This will lead the consumer to use energy without thinking about the consequences, specifically in relation to $CO_2$ emission production and environmental responsibility. Occupants are part of the responsibility when consuming extra energy to operate their homes. Land loans and construction loans and subsidised energy account for much of the energy use in the domestic sector. This can be controlled by limiting energy uses depending on the number of household members and the size of the property. As presented in the analysis section, many questions have been designed to determine factors leading to high energy consumption in relation to floor area and the number of occupants (household size), while some of these questions relate to property area and number of rooms. According to the Ministry of Municipality in Saudi Arabia, the average area of a residential site is 625 m$^2$; only 60% of the site can be built on. This huge area encourages people to build on the entire 60% of the site area as permitted. The survey found that the average area of properties in Saudi Arabia is large compared with similar dwellings in Europe. However, this is because each citizen in Saudi Arabia can expect a free site with an area of 625m² and a loan of 500.000 SR (£82,129.31) with which to build on this site. The free site, and the loan encourage citizens to use the maximum area permitted for construction, resulting in a large-sized property. This unnecessary space will need to be served by electricity (lighting, air conditioning, etc.) and will be used for domestic activities, causing greater energy consumption and $CO_2$ emissions.

In addition, the number of rooms within a property is unusually high. For example, the majority of dwellings in Saudi Arabia have more than five toilets and more than seven bedrooms for a limited number of household members. These numerous rooms require energy for air conditioning, lighting and other activities, resulting in high energy consumption. In addition, the electricity tariff is cheap in Saudi Arabia. People have been encouraged by all these circumstances – electricity price, low cost of construction materials, and free sites with free loans – to construct large dwellings with extensive living areas, leading to high energy consumption as well as high $CO_2$ emission rates.

***Heating, ventilation, and air conditioning:*** Heating, ventilating and air conditioning systems (HVAC) are the largest consumers of energy in these buildings, particularly in harsh climates (Fasiuddin and Budaiwi, 2011). Cooling the indoors is responsible for the highest proportion of energy consumption. According to Taleb and Sharples, air conditioning consumes about 80% of the energy used in domestic buildings in Saudi Arabia (Taleb and Sharples, 2011). The country has a hot climate, containing both arid and humid areas, and this aggressive climate requires extra energy for air conditioning to cool the property to a satisfactory level for human thermal comfort. Since, as shown in the analysis, the majority of respondents use air conditioning in their homes, it is important to create solutions that reduce the energy demand for air conditioning, by using efficient insulation or harvesting solar energy, for example. The significance of such measures becomes clearer when one takes into consideration the harshness of the Saudi climate that makes the operation of cooling systems necessary. About 96% of respondents stated that natural ventilation does not achieve a satisfactory level of thermal comfort.

Based on this result, it is important to find solutions that reduce the energy demand placed on cooling systems, in addition to proposing alternative fuel resources. According to previous studies, there are many possibilities for achieving electricity load-leveling in Saudi Arabia; for example, TES (Thermal Energy Storage, i.e. chilled water storage/ice thermal storage), coupled with a conventional air-conditioning system. It is anticipated that TES can reduce peak cooling-load demand by approximately 30±40% and peak electrical demand by approximately 10±20% (Hasnain and Alabbadi, 2000).

***Lack of public awareness:*** Occupants' behavior is one of the significant factors that control energy consumption in homes (Virote and Neves-Silva, 2012, Hendrickson and Wittman, 2010, Romero et al., 2013). According to Valkila and Saari (2013), "*To mitigate climate change technical advances must be accompanied by greater ecological commitment from consumers, i.e. households*" (Valkila and Saari, 2013). Approximately half the respondents had no knowledge of the concept of sustainable homes or low energy buildings; this lack of awareness creates the perception that there is no scope for energy saving.

***Educational dimension and awareness:*** Education level plays a significant role in general awareness, including awareness of sustainability and low energy housing. According to the central Department of Statistics and Information in Saudi Arabia, educated people comprised about 94.4% of the population in 2013. A public survey involves people with different levels of education, including people who hold a PhD, as displayed in Table 4.1. Meanwhile, illiteracy in Saudi Arabia is low, at about 5.6% in 2013. Most people use the Internet and have access to media facilities to receive messages to heighten awareness. However, the survey results also illustrate a lack of awareness in energy conservation in building, as seen in Figures 4.10 and 4.12. It is now essential to take steps to improve energy savings in the domestic sector. They confirmed that, sustainable homes in Saudi Arabia are important, as is a green and clean environment conserving energy consumption. This figure reflects rising awareness as an important step to be conducted while the public are being educated and awareness is being accepted.

### 4.3.2 Socio-Cultural Blockers That Hinder Sustainable Homes

Socio-cultural blockers to the acceptance of reduced energy consumption for domestic buildings have been taken into account in many recent studies. A study carried out in Liaoning province in China by Feng Dianshu et al. (2010) investigated the barriers to energy efficiency for domestic buildings, and identified the patterns of occupants' consumption of electricity (Dianshu et al., 2010). In order to establish sustainable low energy homes in Saudi Arabia, socio-cultural blockers must be overcome. Some of these barriers have their roots in Islam, but others are cultural rather than religious (Abdullah Eben Saleh, 1998). The barriers based on religion must be respected, but those that are only related to culture can be overcome if they do not meet sustainable requirements, or if they cause high energy consumption. The aim when building sustainable dwellings is to reduce energy consumption and $CO_2$ emission rates as far as possible. However, in order to find the best solutions, many cultural challenges must be taken into account.

Firstly, Islam prohibits socialisation of both genders in one place. Of the many factors identified as being linked to culture and traditions in Saudi Arabia, this section describes those that can affect the style of architectural design in Saudi housing. Hence, it known that cultural factors and traditions in Saudi Arabia influence energy consumption in the domestic sector. For example, most housing in Saudi Arabia is designed to have two main entrances, one for males and another for females, to ensure the traditional separation of the genders.

Moreover, houses are typically designed to include separate guest rooms, one for males and another for females, for the same reason. These rooms are normally spacious, and are served by electricity for cooling and lighting to meet the comfort needs of the occupants. Reducing the number of these rooms to provide one guest room for both genders is a solution, but is prohibited and unacceptable for religious reasons, as seen in the analysis. A possible solution, that would respect the Islamic faith in Saudi Arabia, while minimizing energy consumption, would be to reduce the size of the guest rooms as far as possible, while keeping the genders separated. It is traditional in Saudi Arabia to receive visitors frequently, but guests could be accommodated in an existing seating area, with no need for another room and the consequent additional energy expenditure. Guest rooms are normally allocated to the ground floor, while bedrooms and other seating areas are allocated to the top floor. However, bedrooms and seating areas are used more than guest rooms, so it would be logical to have these on the ground floor, as ground floor rooms consume less energy than top floor rooms, because top floor rooms face direct solar heat, resulting in greater energy requirements to support cooling systems.

Furthermore, there are frequently more bedrooms than needed for the members of the household members. Each bedroom will be served by electricity for cooling; lighting and other personal activities, but each room serves just one or two occupants. The factors highlighted will influence energy demand and lead to excess use of energy. Therefore, altering some traditional aspects of Saudi housing design could reduce domestic energy use. Raising awareness and time are the factors most likely to alter these traditions.

Building size and area are symbols of a person's status or position in society. The figure showing the viewpoints of the respondents on this issue indicates the importance of this factor, as many respondents do not accept a reduction in building size to consume less energy.

### 4.3.3 Engagement With Low Carbon Interventions

Engagement with low carbon building is important due to the need to reduce energy consumption in buildings and to reduce $CO_2$ emission rates (Zhou, 2006, Zhang et al., 2013, Ng et al., 2013). According to Jiang et al (2013), individual behavioral change and engagement with the concept of low carbon buildings depends on a number of factors, including an increase in public awareness of energy issues; policies designed to change behavior; the breaking down of socio-cultural barriers and the establishment of a system for long-term engagement (Jiang et al., 2013). The location of Saudi Arabia and the availability of natural resources creates an advantage that can encourage engagement with low carbon interventions and support the construction of environmentally sustainable buildings. Saudi Arabia is located in a part of the world where the average availability of solar energy is 2200kWh/m² (Alawaji, 2001). Despite this, the use of sustainable technologies of renewable energy (PV) is exceptionally rare

(Taleb and Pitts, 2009). In Saudi Arabia, existing homes can be retrofitted to reduce energy consumption and to engage with low carbon interventions. In addition, future homes can be designed and constructed under the guidance of low carbon criteria to achieve similar levels of sustainability. The details of the engagements for both existing homes and future homes can be summarized as follows:

**Engagement with low carbon interventions for existing homes:** One of the greatest opportunities to reduce energy demand and $CO_2$ emissions lies in retrofitting existing homes to save energy. Only limited solutions can be offered for existing homes, because many effective measures can only be taken at the construction and/or design stage (e.g. efficient, highly insulated roofs and external walls). These limited solutions can consist of (i) installing a PV system, (ii) installing a PV storage tank, (iii) replacing the poor single glaze with an efficient double or triple glaze, and (iv) installing efficient shading devices around the building and its external windows. These solutions can reduce the energy demand by up to 34% compared with the total energy consumption of the building (Aldossary et al., 2014a).

The survey identified the ability of people to retrofit their existing homes in terms of energy saving, leading to minimizing costs and $CO_2$ emissions as far as possible. The majority of respondents agreed in principle with the idea of retrofitting their existing homes, but it is important to recognize factors that can prevent them from doing so. Firstly, in order to retrofit existing dwellings, it is necessary to promote a product and create a market for sustainable industry as well as provide facilities for people. Products that reduce energy demand in buildings are lacking, as seen in the survey, while a marketplace for these products must be established and advertised to encourage people to retrofit their homes and reduce energy demand. The availability of these products is essential to support the construction industry in terms of energy saving, but the Saudi market lacks such products. The majority of respondents agree or strongly agree that there is a shortage of sustainable products, such as PV in the Saudi market, and they understand that the market should be established and regulated in order to promote the construction of sustainable buildings. More specifically, as seen in the analysis, the majority of respondents agree or strongly agree with the idea of installing PV systems in their dwellings in order to use solar radiation to generate electricity instead of burning fossil fuel. However, these systems need to be promoted in the Saudi market. Based on these results, there is no general barrier that prevents existing domestic buildings from being retrofitted and becoming more efficient in terms of energy savings in Saudi Arabia. This substantial opportunity must be exploited to improve existing domestic buildings as much as possible.

**Engagement with low carbon interventions for future homes:** The main barriers to engagement with low carbon interventions for future homes are (i) level of awareness and (ii) socio-cultural blockers. There is a lack of awareness in Saudi Arabia regarding the importance of establishing low energy buildings or sustainable, green buildings, as seen in this survey analysis. The public should be educated regarding the concept of sustainable, low energy building, and in the importance of reducing energy consumption and $CO_2$ emissions. As seen in the survey, more than half the respondents have some understanding of the importance of constructing sustainable buildings; however they need to be encouraged to design their future homes according to sustainability criteria, while establishments and facilities for sustainable industry should be promoted.

One of the objectives of this research is to assess peoples' ability to understand the need for sustainable, low carbon homes in the future. When briefly explaining this concept and suggesting some issues related to low energy houses in different questions, it was found that the majority of respondents either agree or strongly agree that future dwellings in Saudi Arabia must be designed in a manner that leads to saving energy and minimizing $CO_2$ emissions. Furthermore, a majority of respondents (60%) agreed or strongly agreed that a sustainable design framework for homes should be made compulsory by the government. This figure indicates government sectors such as the Ministry of Municipality must take steps to establish a policy of constructing low energy buildings and to supervise and approve the plans of all future buildings, in order to ensure that they are designed according to sustainable criteria, to save energy and minimize $CO_2$ emission rates. The negative aspect of the findings were that some criteria that need to be taken into account were not universally acceptable: for example, half of the respondents disagreed or strongly disagreed with the idea of reducing the size of buildings.

Based on these figures, sustainable low energy homes can be established effectively by (i) creating sustainable establishments; (ii) supporting the market for sustainable products; (iii) raising public awareness; (iv) making sustainable criteria for future building compulsory; and (v) establishing a framework for designing low carbon homes suited to the Saudi Arabian climate and context.

### 4.3.4 Environmental Assessment And Regulatory Compliance Environment

Many studies have highlighted the regulatory compliance environment and environmental assessment procedures necessary to achieve low carbon buildings (Kajikawa et al., 2011, Gou and Lau, 2014). In many countries policies relating to building energy are moving quickly toward regulatory levels that require close to zero energy or zero carbon emission buildings (Kapsalaki and Leal, 2011). Despite the increasing stringency of building energy regulations, non-compliance still exists in practice (Pan and Garmston, 2012); nevertheless some developed countries have established a regulatory target (net zero carbon) aimed at achieving a compliance environment (Kirsten Engelund Thomsen, 2008). According to Murphy (2012), in jurisdictions across the world, the form of building regulations is one aspect of the policy response to both climate change and energy security (Murphy, 2012). There is a pragmatic shift, in both developing and developed countries, towards employing building energy regulations and standards codes in order to minimize energy consumption in buildings (Vine, 2003, Iwaro and Mwasha, 2010, Radhi, 2009). Pan and Garmston (2012) examined the profile of compliance with the building energy regulations for newly-built domestic buildings. They found the compliance profile was influenced by several factors, including the Standard Assessment Procedure (Pan and Garmston, 2012), but that regulation can face some cultural barriers. Iwaro and Mwasha (2010) recommend some suggested solutions to the problems (e.g. investing in building energy regulatory; technology subsidies; organisational constraints and public information campaigns) that can face attempts to implement the regulations for building energy in developing countries (Iwaro and Mwasha, 2010).

It is extremely important to establish a target regulatory compliance environment for low carbon buildings in the Saudi Arabian domestic sector, which takes into account both social and cultural factors, and the issues raised by the country's hot climate. Achieving this target depends on identifying factors relating to high energy consumption, local climate conditions and the cultural barriers that limit successful widespread construction of low carbon homes in Saudi Arabia. In order to benefit from this study and to identify the factors that cause high energy consumption in Saudi Arabia, it should be clearly understood that domestic buildings consume over 50% of this energy, according to the report of the Ministry of Electricity in Saudi Arabia (Electricity, 2010). This shows the importance of a robust regulatory compliance environment and the huge benefits (economic, environmental, and social), which can be derived from reducing the energy demand in residential buildings. However, before presenting these benefits of an effective compliance environment, it is important to offer solutions and suggestions for implementation, which present the output benefit in strategic (i.e. economic and environmental) terms, as well as personal ones (i.e. as they affect individual homeowners).

According to the Ministry of Electricity in Saudi Arabia, electricity bills sent to consumers are already subsidized (Alyousef and Stevens, 2011) at a percentage of their actual cost, due to the government's policy of supporting household energy use in the domestic sector. This policy can be replaced by another approach; namely that of encouraging house owners to retrofit their dwellings through: (i) installation of PV panels at the expense of the Ministry of Electricity, as an alternative to the subsidizing of electricity bills; (ii) encouraging people to retrofit their dwellings by increasing public awareness of the reduction in electricity consumption which this would achieve, whilst maintaining comfortable conditions; and (ii) establishing a governmental approach that manages the sustainability of buildings in Saudi Arabia, as reflected in stringent policies and regulations to assist in implementing and monitoring energy savings and $CO_2$ emission reduction across the country. According to Ruiz Romero et al (2012), recent successes in adopting on-site renewables has mostly been due to public financial incentives (Ruiz Romero et al., 2012). The conversion of the energy industry to more efficient and sustainable electricity production increases the importance of distributed generation from renewable sources (e.g. PV) (Richter, 2013). Incentives and the implementation of solutions (efficient form and fabric) for existing houses and flats across Saudi Arabia will certainly require complementary measures. However, further discussion remains necessary in order to formulate policies that can help in the adoption of these solutions.

In economic terms over 50% of energy is consumed by the residential sector. This figure represents both a challenge and a great opportunity to re-use this burned fossil fuel for other investments. For example Saudi Arabia is rich in solar radiation (Rehman et al., 2007); therefore, this natural resource could be used to meet people's needs as far as possible. By both reducing the energy demand and using a natural resource to satisfy the needs arising from people's domestic activities, the country can reduce the amount of burned fossil fuel and increase income on a strategic scale. From an environmental perspective, many benefits can be gained from establishing friendly (sustainable) domestic buildings in Saudi Arabia. A huge amount of $CO_2$ emission is produced by Saudi domestic buildings, as compared with 25 European countries (Aldossary et al., 2014a, Aldossary et al., 2014b). However, a dramatic reduction in energy will reduce the amount of $CO_2$ emissions. Energy reduction is needed not only to save on the cost of electricity, but also to fulfill the responsibility of both governments and individuals to protect the environment from $CO_2$ emissions.

## 4.4 Summary

This study has presented public perceptions regarding sustainable homes in Saudi Arabia and identified the factors leading to high energy consumption, as well as the cultural barriers preventing the establishment of sustainable homes in Saudi Arabia. An in-depth survey was used as the main methodology, taking into account the need to reach people in different age groups and at different educational levels, to obtain a realistic image of public perceptions. The results have illustrated and identified many factors leading to high energy consumption in the residential sector in Saudi Arabia. These factors were discussed individually to provide some guidance towards solutions for avoiding high energy consumption and minimizing $CO_2$ emission rates as far as possible.

Furthermore, the study has identified some cultural barriers that prevent the establishment of sustainable homes in Saudi Arabia, some of which are related to Islam. Solutions were presented along with their economic, social and environmental benefits and suggestions for their implementation.

# Chapter 5 : Site Visit To Case Studies; Investigations, Analysis And Solutions For Existing Homes

***This chapter has been published in two leading journals:***

Aldossary N, Rezgui Y, Kwan AS, Domestic energy consumption patterns in a hot and arid climate: A multiple-case study analysis, *Renewable Energy* , 62 (2014) 369-378 ISSN 0960-1481 10.1016/j.renene.2013.07.042

Aldossary N, Rezgui Y, Kwan AS, Domestic energy consumption patterns in a hot and humid climate: A multiple-case study analysis, *Applied Energy* , 114 (2014) 353-365 ISSN 0306-2619 10.1016/j.apenergy.2013.09.061

***And international conference in USA:***

Aldossary N, Rezgui Y, Kwan AS, Energy consumption patterns for domestic buildings in hot climates using Saudi Arabia as case study field: multiple case study analyses, *Computing in Building and Civil Engineering (2014)* , (2014) 1986-1993 ISBN 9780784413616 10.1061/9780784413616.246

## 5.1 Introduction

This chapter analyses and discusses domestic energy consumption patterns in Saudi Arabia ; a country characterised by its hot climate and its geographical location in a global region renowned for its high energy consumption and carbon emission rates. For this purpose, eighteen existing and occupied dwellings were selected from regions across Saudi Arabia as it was described in the methodology chapter 3 section 3.3.2 pp. 68-75. The sample includes six domestic buildings in the scorching, arid climate of Riyadh, six domestic buildings in the hot but humid weather of Jeddah City, and six domestic buildings in the hot, dry mountainous area of Al Baha City. The investigation will focus on analysing their average domestic energy consumption based on (a) monthly electricity bills, (b) user behaviour captured through interviews with the selected properties' occupants, and (c) detailed energy modelling and simulation using IES-VE software. Resulting high energy consumption patterns are then discussed focussing on building design (form and fabric) and user behaviour.

This chapter aims to (i) investigate the energy consumption patterns in different climates of Saudi Arabia, using a multiple case study approach in the mintioned cities, and employing an established energy simulation software tool; (ii) identify the design weaknesses (form and fabric) that translate into high energy consumption patterns; (iii) suggest retrofitting solutions based on the identified weaknesses in order to reduce energy consumption in existing domestic buildings; and (ix) validate the results using an energy simulation tool.

The chapter will be divided into four main categories; introduction, the hot and humid climate (city of Jeddah); the hot and arid climate (city of Riyadh) hot and arid climate with mountainous topography (City of Al-Baha) and finally summary.

## *5.2* Hot And Humid Climate: City Of Jeddah

Jeddah city, which has a hot and humid climate, was chosen as the location for the case study. Jeddah is the main port and is located on the west coast of Saudi Arabia, on the Red Sea, at latitude 21_300N and longitude 39_100E (Said et al., 2003). Table 5.1 presents the Monthly averages for temperatures and humidity levels in the city:

**Table 5.1 Jeddah City Climate Data (CDOS, 2008)**

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Max Temperature** | 32 | 35 | 39 | 42 | 42 | 48 | 45 | 41.5 | 42 | 43 | 38 | 36.5 |
| **Min Temperature** | 13 | 15.4 | 18 | 19 | 20 | 23.4 | 24.8 | 25 | 23.8 | 20 | 20 | 17 |
| **Relative humidity** | 59 | 56 | 60 | 58 | 56 | 58 | 49 | 52 | 66 | 61 | 65 | 51 |

Three houses and three flats located in the city were selected for individual examination by IES-VE to achieve the research goals. The selected properties are described below according to their architectural characteristics and discussed in relation to their user profiles.

### 5.2.1 Description of the Houses

The three houses selected are newly built, with a maximum age of two years, and are located in different areas; one in the east and the other two adjacent to one another in the north west of Jeddah. Table 5.2 below presents the details for each house:

**Table 5.2 Description Of The Selected Houses**

| Type of property | Number of floors | Total built Area m² | Number of Occupants |
|---|---|---|---|
| **House (A)** | 3 Floors | 338.7 | 7 adults 2 children |
| **House (B)** | 3 Floors | 338.7 | 2 adult 3 children |
| **House (C)** | 2 Floors | 772.3 | 5 adults 2 children |

Houses (A) and (B) have the same design style and are located side by side. Each house comprises three floors and their plans are identical but symmetrical along their long axes. The first floor plan for each has two main entrances, a front entrance for males and a side entrance for females (Figure 5.1). Also on the ground floor there are two separate guest rooms, one for males and another for females, a single dining room, two bathrooms and one kitchen in each house. This design style is common in Saudi Arabia and reflects Saudi Muslim culture. The first floor includes one en-suite master bedroom , four additional bedrooms, two bathrooms, a seating area for the family and a corridor. The third floor has a store room, a bathroom, a laundry room and a bedroom for the housekeeper. The remainder of this floor has not been turned into rooms because the regulations in Saudi Arabia for houses allow only two built-up floors and a few rooms on a third floor not in excess of 30% of the total built area.


**Figure 5.1 Design Plan Of Houses (A) And (B); (Ground, First And Second Floors)**

In contrast, house (C) Is much larger and has only two floors. The ground floor contains two main entrances similar to houses (A) and (B), with some additional rooms. It contains two guest rooms for males including private facilities, one private guest room for females also including private facilities, a kitchen and a lounge and some bed rooms. The second floor contains two master bedrooms with en-suite facilities, four bedrooms including two bathrooms, one lounge area and one seating area (Figure 5.2).

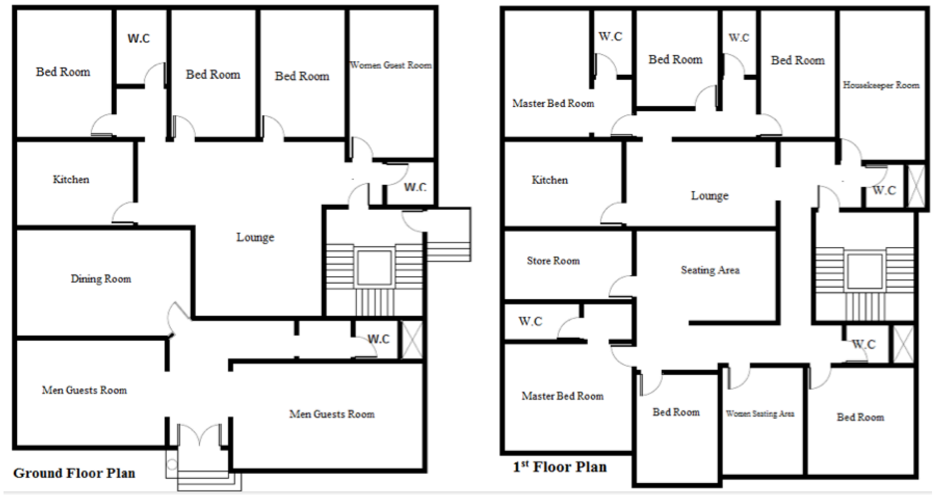



**Figure 5.2 Design Plan Of House (C)**

The construction material used as the building fabric for the three houses also differes; houses (A) and (B) share the same construction materials. Table 5.3 presents these materials according to the official construction plans, while Table 5.4 presents the construction materials used in house (C).

**Table 5.3 Building Fabrics For Houses (A) And (B)**

| Element | Description | Thickness /cm | R-value $m^2k/W$ | Thermal Mass KJ/ $m^2k$ |
|---|---|---|---|---|
| **External Wall** | Mortar- brick -mortar | 24 | 0.36 | 158.9 |
| **Internal Partitions** | Mortar-Inner brick-mortar | 24 | 0.18 | 92.4 |
| **Roof** | 6 layers (tiles, mortar, sand, insulation, reinforced concrete) | 43 | 0.30 | 225 |
| **Floor** | 7 layers (ceramic, mortar, sandstone, concrete, insulation, basement concrete and basement stone) | 50 | 0.2 | 190 |
| **Windows** | Single glazing | 1 | 0.18 | --- |
| **Doors** | Wooden door | 4 | 0.2 | 22.7 |

**Table 5.4 Building Fabric For House (C)**

| Element | Description | Thickness /cm | R-value $m^2k/W$ | Thermal Mass KJ/ $m^2k$ |
|---|---|---|---|---|
| **Elevation Wall** | Stone- mortar- hollow brick- mortar | 27 | 0.4 | 158.9 |
| **External Wall** | Rock- brick inner leaf -mortar | 24 | 0.59 | 158.9 |
| **Internal Partitions** | Mortar-brick-mortar | 14 | 0.18 | 92.4 |
| **Roof** | 6 layers (tiles, mortar, sand, insulation and reinforced concrete) | 40 | 0.33 | 225 |
| **Floor** | 7 layers (ceramic tiles, mortar, sandstone, concrete, Asphalt insulation, basement concrete and basement stone) | 50 | 0.2 | 190 |
| **Windows** | Single glazing | 1 | 0.18 | --- |
| **Doors** | Wooden door | 4 | 0.2 | 22.7 |

### 5.2.2 Description Of The Flats

The three flats selected are on the first and second floor of a newly built apartment building (three years old) located in the south east of Jeddah. Table 5.5 below presents a description of each flat.

**Table 5.5 Description Of The Selected Flats**

| Type of property | Location in the Building | Total Area m² | Number of occupants |
|---|---|---|---|
| **Flat (A)** | First Floor | 210.6 | 5 adults 2 children |
| **Flat (B)** | First Floor | 210.6 | 2 adults and 3 children |
| **Flat (C)** | Second Floor | 222.36 | 6 adults and 3 children |

The specification of the flats is approximately the same as that given for the houses but the sizes are different. Each flat contains two guest rooms, one for males and the other for females, including bathroom facilities. Each flat contains a dining room, a kitchen and a seating area. There is a master bedroom, two additional bedrooms, and further facilities in each flat. Each flat also includes one room for the housekeeper who works there (Figure 5. 3).


**Figure 5.3 Design Plan Of Flats (A), (B) And (C)**

Table 5.6 details the construction materials used for the building fabric of the flats, according to the official construction plans.

**Table 5.6 Building Fabric For Flats (A), (B) And (C)**

| Element | Description | Thickness /cm | R-value $m^2k/W$ | Thermal Mass KJ/ $m^2k$ |
|---|---|---|---|---|
| **External Wall** | Mortar- concrete brick-mortar | 24 | 0.59 | 158.9 |
| **Internal Partitions** | Mortar-common brick-mortar | 24 | 0.18 | 92.4 |
| **Roof** | 6 layers (tiles, mortar, sand, insulation and reinforced concrete) | 40 | 0.6 | 255 |
| **Floor** | 7 layers (ceramic, mortar, sandstone, concrete, insulation, basement concrete and basement stone) | 50 | 0.2 | 190 |
| **Windows** | Single glazing | 1 | 0.18 | --- |
| **Doors** | Wooden door | 4 | 0.2 | 22.7 |

### 5.2.3 Occupant User Profiles

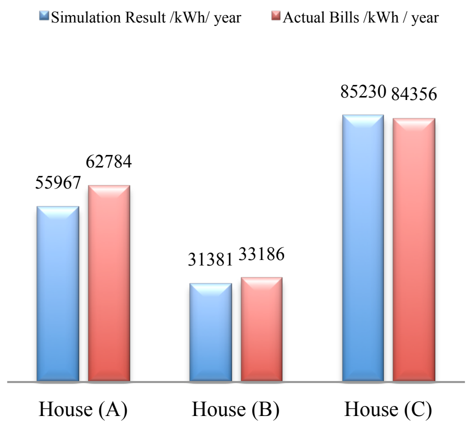
The uses of the rooms were discussed with each household individually to establish a particular user profile for each property. Based on these data the user profiles were found to differ; the ages of the occupants in houses (A) and (B) vary, and the occupant in house (B) disclosed that there were some rooms on the second and third floors that are not used, furnished, or supplied with electricity. Moreover, the occupants of flat (C) differ from those in the other two flats. The main occupant of flat (C) is a retired man who has five other adults and three children also living in his flat. The usage of the occupied bedrooms is approximately the same in all of the houses and flats; all of the occupants tend to sleep at night and either work or attend school in the daytime. Generally there is also a common use of rooms such as the seating area, although the durations of use vary between families.

### 5.2.4 Analysis And Results

As noted above, the energy consumption in the selected houses and flats was simulated and analysed using the IES-VE tools. The simulations were based on the design of each case study, the building fabric used and the user profile. The results of the simulation provide the energy consumption figures as well as the individual $CO_2$ emissions for each property. These results can then be compared with the actual energy consumption, as stated in the utility bills for 2011, with analyses divided into three main sections: an analysis of the houses, analysis of the flats, and the $CO_2$ emissions for both the houses and the flats.

#### *5.2.4.1 Analysis of the Houses*

Based on the simulation results and according to the actual utility bills from 2011, the annual energy consumption differs between houses, with the average annual electrical energy consumption ranging from 109 kWh / m² to 185.4 kWh / m². Figure 5.4 illustrates a comparison between total annual electrical energy consumption for each of the three houses (IES-VE simulation result and utility bills), while Figure 5.5 illustrates the average annual electrical energy consumption according to kWh / m². It can be seen that house (C) has the highest total energy consumption, probably because it is larger than the others. On the other hand this value is average when compared with the IES-VE simulated results for houses (B) and (C) as measured according to kWh / m² (see Figure 5.5). It is worth noting that the total energy consumption, comparing the utility bills and the simulation results, is approximately the same for all three houses (see Figure 5.4).



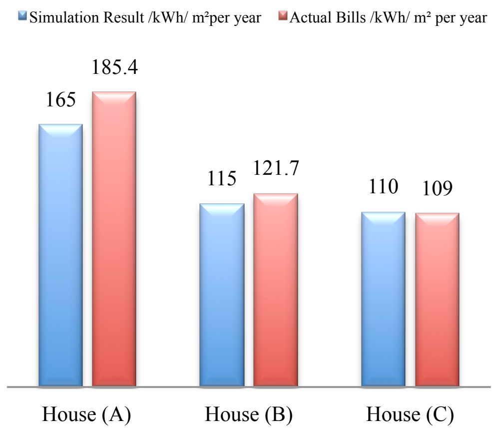




**Figure 5.4 Total Annual Energy Consumption /kWh** **Figure 5.5 Annual Energy Consumption /kWh/ m²**

Monthly energy consumption figures according to the IES-VE simulation results are compared with the utility bills for 2011 and displayed in Figures 5.6, 5.7 and 5.8. For all three houses the highest energy consumption is expected to occur during the summer when the weather is very hot, requiring extra energy to run the air conditioning for interior cooling. The actual behaviour does differ in some instances; for example in house (A), according to the utility bills, the energy consumption dropped in June. The reason for this, identified through discussion with the occupant of the house, was that his family travelled abroad for a few weeks in the summer. Moreover, this same household had visitors during the remainder of the summer leading to more activity at these times, as shown in the actual bills (Figure 5.6). This situation is the same in house (B) as shown in Figure 5.7 which indicates that the energy consumption, according to the utility bills, dropped dramatically in July (summer time).

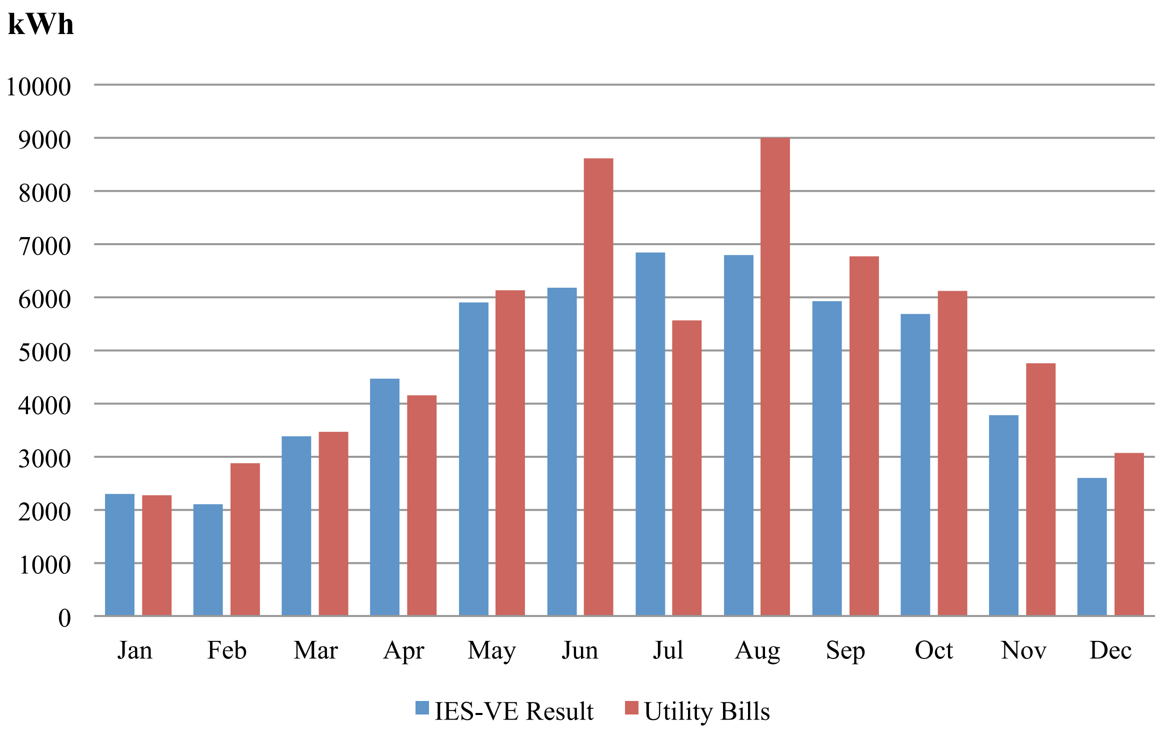



**Figure 5.6 Monthly Energy Consumption / kWh House (A)**

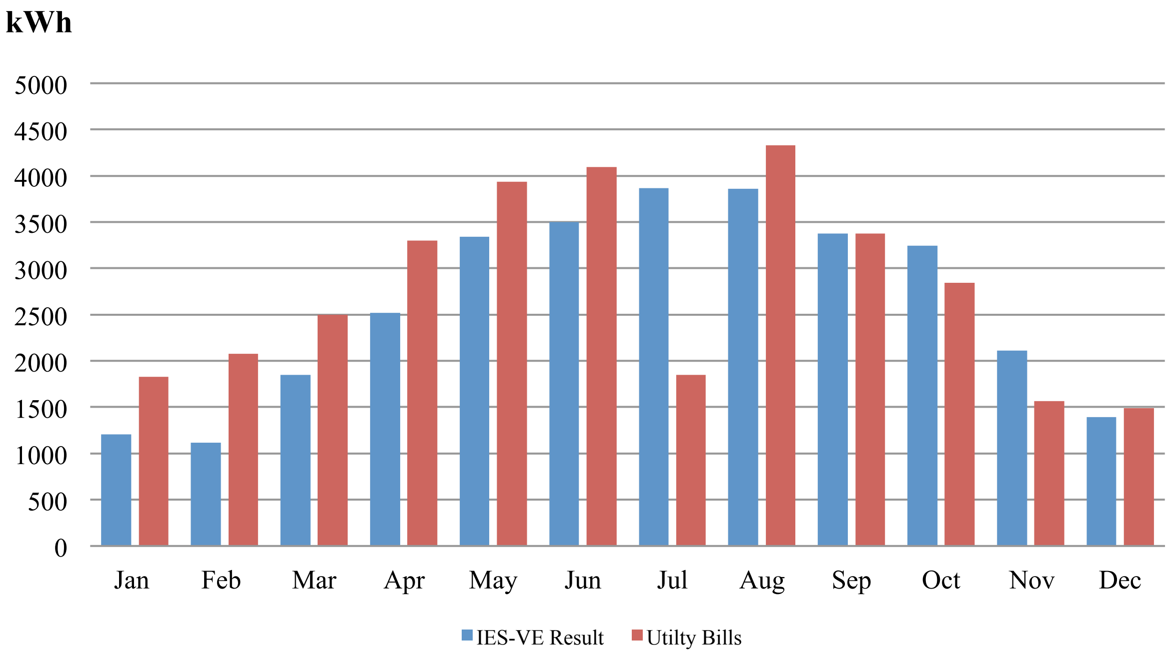



**Figure 5.7 Monthly Energy Consumption / kWh House (B)**

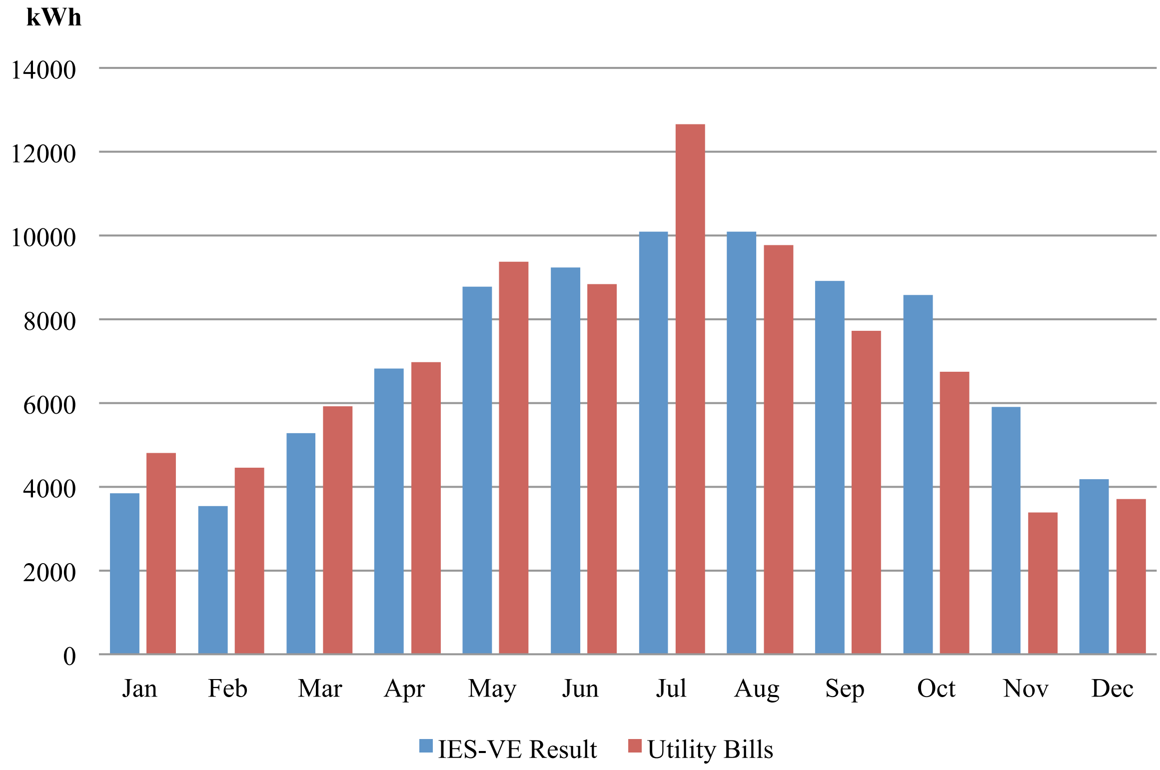



**Figure 5.8 Monthly Energy Consumption / kWh House (C)**

Figures 5.9, 5.10 and 5.11 reflect the actual energy use. The IES-VE results indicate that 76% to 86% of the total energy is consumed for air conditioning purposes because the heat and humidity temperature in this area may cause discomfort. The overall energy consumption in house (C) is the lowest but the electricity consumption (kWh/year) is the highest because this house is larger than the others. House (C) requires 76% of total annual electricity demand to operate the cooling system; 64,774 kWh per year of electricity is consumed for cooling. The varying uses of rooms in the properties create differences in energy consumption, for example house (C) contains two large guest rooms for men, but the daily use of these rooms is relatively light in comparison with other rooms. Generally the results illustrate that over three quarters of electricity consumption is for air conditioning. This finding is in line with previous studies such as (Akbari H at el 1996 cited in (Taleb and Sharples, 2011). It reveals the extent of the challenge faced by those seeking to legislate and design practical methods to assist in reducing energy consumption in hot and humid climates. The bulk of the remaining energy is consumed by Auxiliary energy, pumps energy and heating for domestic hot water (DHW).

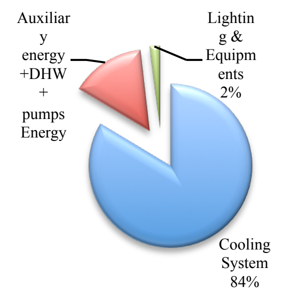



Figure 5.9 Energy Use In House (A)

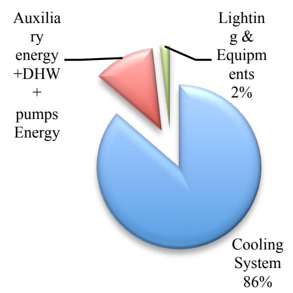



Figure 5.10 Energy Use In House (B)

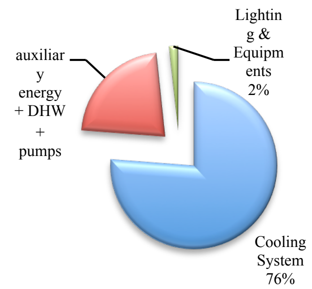



Figure 5.11 Energy Use In House (C)

### *5.2.4.2 Analysis of the Flats*

The total annual electricity consumption varies from one flat to another depending on the floor area and occupant usage. Figure 5.12 illustrates the total annual electricity consumption for all three flats. It can be seen that flat (C) (with the retired gentleman) has the highest electricity consumption according to both the IES-VE simulated result and the actual utility bills. Overall there is a good correlation between the IES-VE simulated results and the actual utility bills. Figure 5.13 illustrates energy consumption according to kWh/m² per year, revealing that the average electricity consumption in the flats varies between 114 kWh /m² per year and 166 kWh / m² per year based on the IES-VE results and actual utility bills.

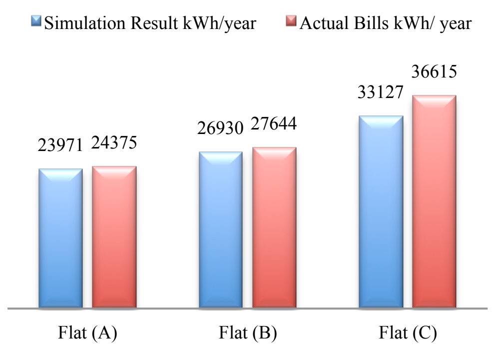



**Figure 5.12 Total Annual Electricity Consumption For Flats /kWh**

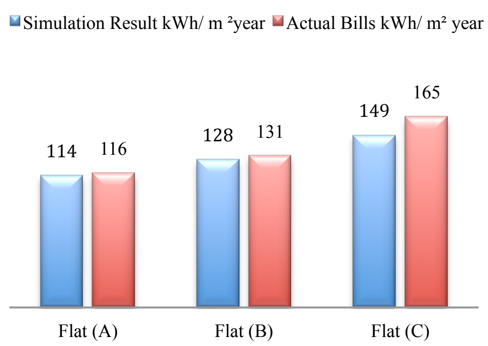



**Figure 5.13 Annual Energy Consumption kWh/ m² For Flats**

Some of the electricity consumption behaviour is reflected in the utility bills and IES-VE simulation results; Figures 5.14, 5.15 and 5.16 illustrate monthly electricity consumption according to the utility bills and IES-VE simulation results, and show a variation in the results between flats. Whilst flat (C) has the highest energy consumption, the monthly energy consumption is approximately equal between flats (A) and (B) over the course of the year; however in flat (A) in June, the energy consumption decreased because the occupants travelled abroad during the summer. The results indicate that the highest energy consumption for the flats is over the summer period, during the hottest season when more air conditioning is required.

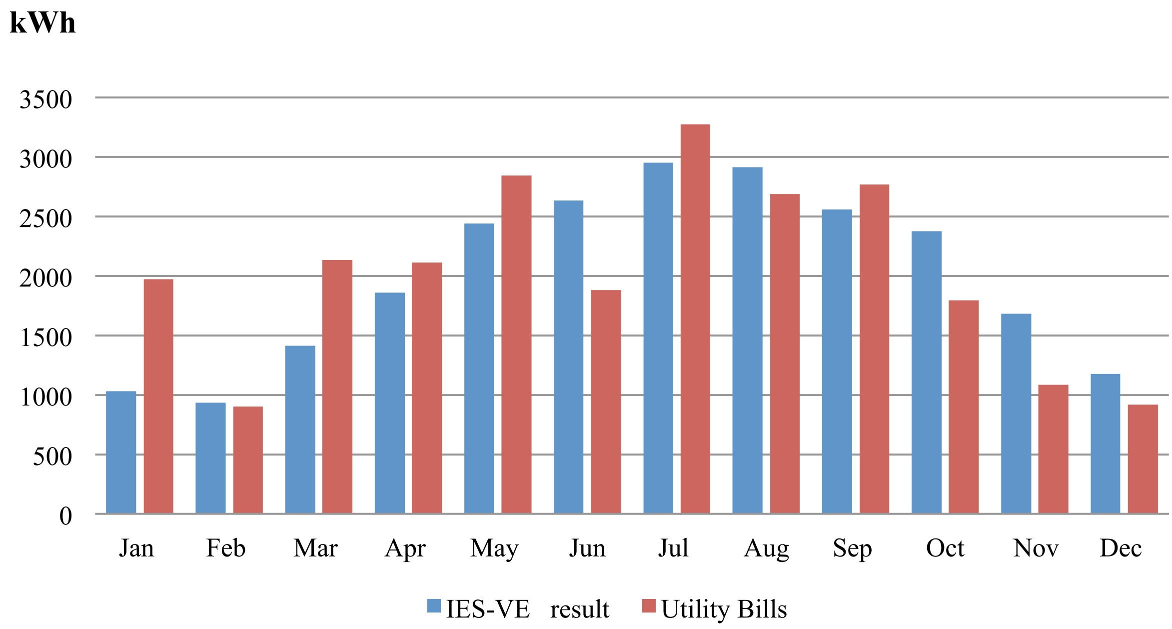



**Figure 5.14 Monthly Energy Consumption / kWh Flat (A)**

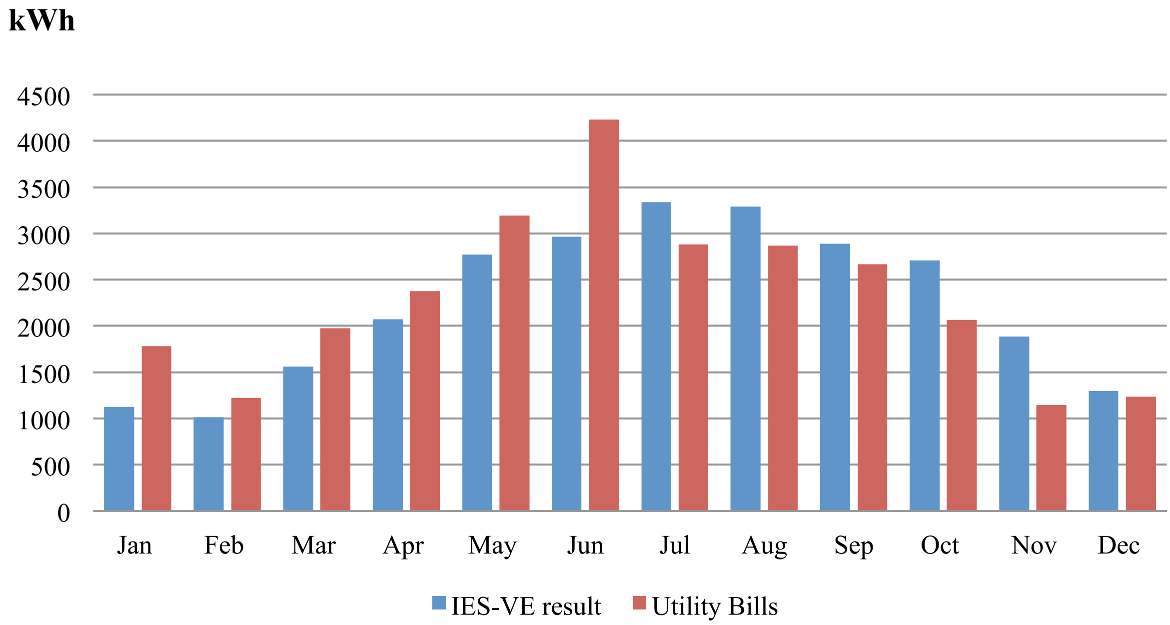



**Figure 5.15 Monthly Energy Consumption / kWh Flat (B)**

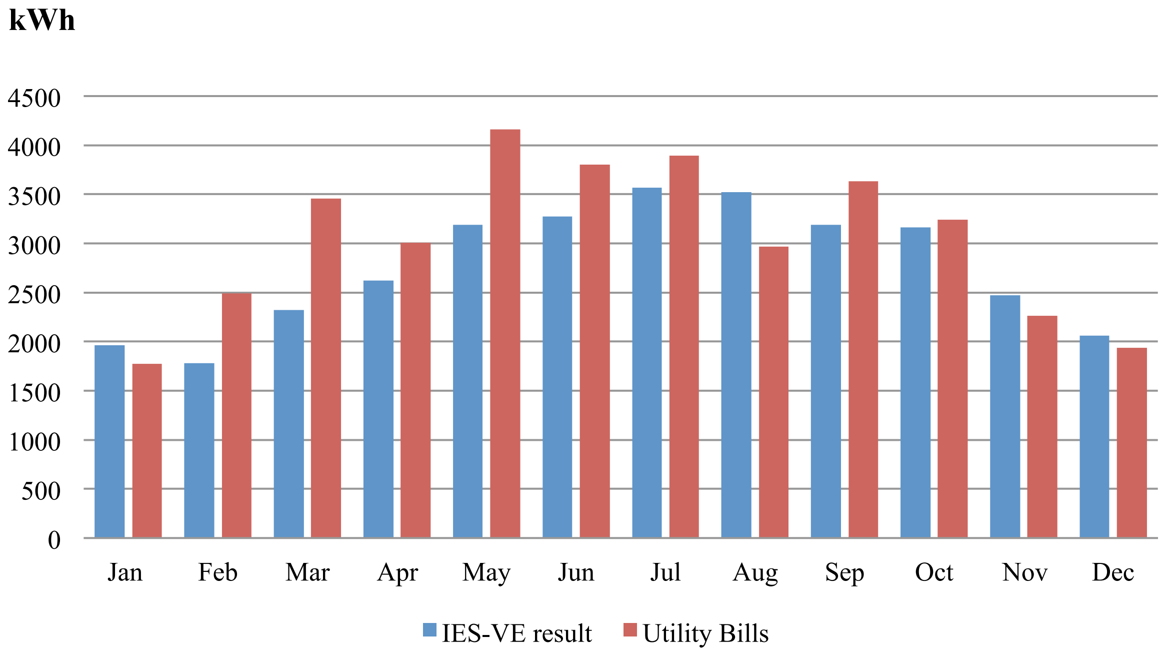



**Figure 5.16 Monthly Energy Consumption / kWh Flat (C)**

The most important aspect of the simulation result is that it reveals the purpose of the energy consumption. As with the houses, the IES-VE simulation result shows the highest proportion of energy consumption for all three flats is that devoted to air conditioning. Figures 5.17, 5.18 and 5.19 illustrate that electricity consumption for the cooling system (air conditioning) ranges from 61% to 78%. The Auxiliary energy, pumps energy and domestic hot water system require an average of 23.6 % of the energy used, whilst lighting and equipment reflect the lowest energy consumption.

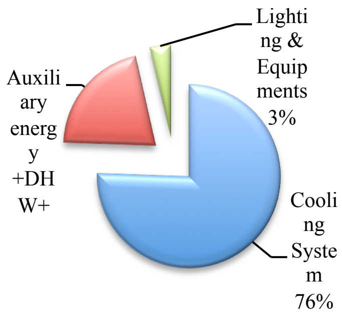



**Figure 5.17 Energy Use In Flat (A)**

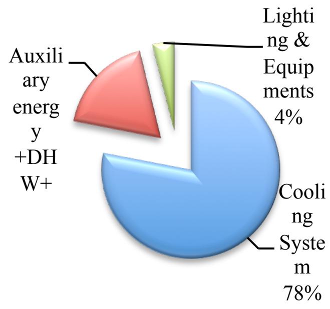



**Figure 5.18 Energy Use In Flat (B)**

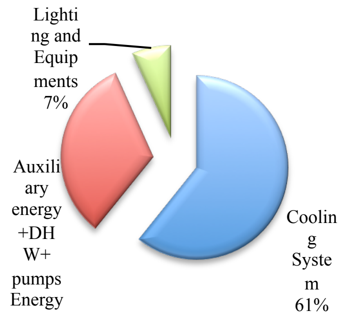



**Figure 5.19 Energy Use In Flat (C)**

### *5.2.4.3 $CO_2$ Emissions*

The annual $CO_2$ emissions for these simulated houses and flats are illustrated in Figure 5.20. As house (C) is the largest and has the highest energy consumption of the selected properties, it can be clearly seen that it produces the highest $CO_2$ emissions. From an environmental perspective, this level is too high in comparison with the average $CO_2$ emissions in European countries per capita, i.e. 44,066 kg per annum for house (C). As there are nine occupants in this house, the $CO_2$ emission per capita is about 4,896kg (4.8 tonnes), which is nearly double the average $CO_2$ emission per capita of the 25 EU member states (about 2.5 tonnes) (Doukas et al., 2006). High energy consumption results in high $CO_2$ emissions, consequently a reduction in the levels of energy consumption and the amount of fossil fuel being burnt will lead to a reduction in $CO_2$ emissions.

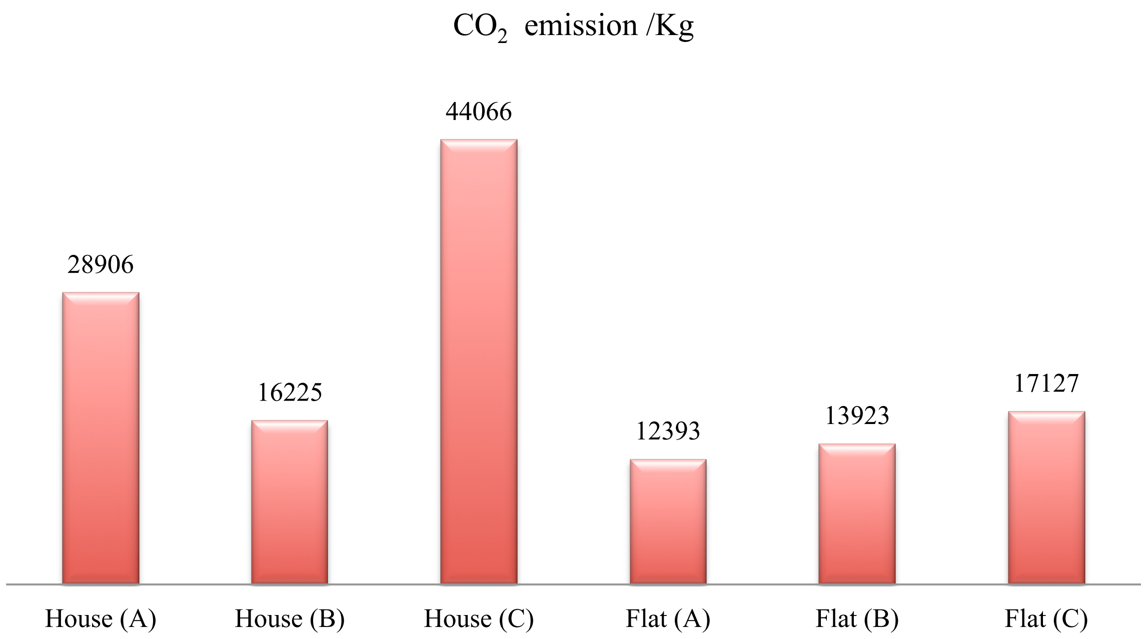



**Figure 5.20 Annual $CO_2$ Emission /Kg Of The Selected Properties**

Finally, in summarising the findings it is acknowledged that the average energy consumption varies between the houses and the flats. The average energy consumption for the houses in the hot and humid climate in Saudi Arabia ranges up to 185.4 kWh /m² per annum, compared with up to 166 kWh /m² per annum for the flats. It is important to state that the high average energy consumption does not reflect high total energy consumption at the property. The high energy demand relates to the area covered by the property. The principal finding is that the majority of the energy consumed is required to drive cooling systems, as shown by all six properties.

### 5.2.5 Discussion

This section is divided into three main parts: firstly it discusses the average energy consumption in domestic properties in Jeddah city, based on the analysed properties; secondly it discusses the weaknesses in architectural design in the properties and examines sustainable architectural principles that may be employed to resolve those issues; and finally it proposes cost-effective solutions that will impact on the case study properties and on the potential for altering similar houses and flats.

#### *5.2.5.1 Energy consumption*

The research results indicate that the average energy consumption for residential units in hot and humid climates is up to 185.4 kWh per m² per annum for a typical house, and up to 166 kWh /m² per year for a typical flat. The biggest problem facing the occupants, according to these case studies, is how best to control the high electricity consumption of the cooling system, especially during the summer season; (approximately 75% of electricity is consumed by the cooling system). This can be achieved using optimal architectural techniques designed to keep the indoor temperature cool for the maximum duration possible.

Furthermore, approximately 20% of energy is being consumed for Auxiliary energy, pumps energy and to produce domestic hot water (DHW). An optimal solar radiation system could play a significant role in reducing the energy consumed for DHW by heating the domestic water in tanks located at the top of the buildings.

The houses and flats analysed all have high $CO_2$ emissions. According to the Energy Information Administration, 2004 cited in (Doukas et al., 2006) , $CO_2$ emission per capita in Saudi houses is too high compared to $CO_2$ emissions per capita in 25 EU member states. Protection of the environment can only be achieved in the future if more sustainable domestic buildings are designed.

Many benefits can be gained by reducing energy consumption in domestic buildings in Saudi Arabia. From an environmental perspective, the reduction in energy consumption in the domestic sector will reduce the use of, and reliance on, fossil fuel (i.e. oil) and hence reduce $CO_2$ emissions. From a financial perspective, reducing energy consumption will minimise annual electricity bills and increase households potential to invest in cleaner energy sources. From a societal perspective, increased awareness may lead to more sustainable lifestyles and occupants' behaviour. Below are details of the weaknesses identified in the analysed houses and flats.

#### *5.2.5.2 Weaknesses in architectural design*

Evidence suggests that residential buildings should be designed according to optimal sustainable architectural principles and efficient construction materials to reduce energy consumption and $CO_2$ emissions (Radhi, 2010, Taleb and Sharples, 2011, Anna-Maria, 2009, Cutler et al., 2008, Al-Sallal et al., 2012, Chel and Tiwari, 2009). However, the high energy consumption indicated by the results from all six case study properties reveals a lack of sustainable architectural principles in all cases. The architectural principles currently available are summarised as follows:

- ***Building envelope:*** It was found, through analysing the properties, that the R-value of the building fabrics being used is too low. The resistance of the house envelope is crucial in stopping, or at least slowing, the hot air as it passes from the external atmosphere to the interior. Optimum design of building fabric (thermal insulation) plays a main role in reducing energy demand and achieving sustainability in buildings, according to researchers (Bojic et al., 2002, Li and Chow, 2005, Fontanini et al., 2011, Dombaycı et al., 2006). Lack of appropriate building fabric is a feature of the houses and flats examined; the external walls share the same layers (mortar, brick and mortar), which comprise the house envelope. This materials profile is consistent with a lack of resistance to external temperatures. The only exception was in the case of house (C), which contained stone in the main elevation of the building. The official construction plans and simulated models reflect the poor design of the building fabric in the roofs, flooring and external walls. The R-value of the roof and the floor was also overly low; indeed, the ratings for the roof materials ranged between 0.18 $m^2k/W$ and 0.59 $m^2k/W$.

  In addition, it was found that single glazing is in use at all of the case study properties. This in turn creates a higher demand for air conditioning. A suitable design for windows would go some way to reducing this demand (Pisello et al., 2012). An efficient glazing system, such as triple-glazing could reduce the transmission of direct-beam solar irradiation and the heat gains from the ambient environment, while maintaining adequate levels of daylight within the building's interior (Askar et al., 2001, Tahmasebi et al., 2011).

- ***Building size and shape:*** As shown in all of the case study properties, the residential units are often too big for one family; the average Saudi family is about 6.2 people according to the Central Department of Statistics and Information in Saudi Arabia. The unused spaces in the houses are often also lighted and air-conditioned, thereby demanding extra energy and producing extra $CO_2$ emissions. As mentioned above, Saudi houses or flats are allocated so much space due to the local culture and expectations of the social community, which require separate guest rooms for men and women. Such a culture is in opposition to sustainability, but this feature of property design will be difficult to change because it is rooted in religion and tradition. The findings also suggest that the shape of the houses and flats also has an impact; each building has a flat roof which directly faces the full heat of the sun. This means that extra energy is required to cool the rooms that are situated on the top floor.

The building size should not exceed human activity requirements. This can be simply inferred on the basis of the number of household members in each property. In Saudi Arabia, social status plays a significant role in dwelling design. Land values in the country are increasing. At the same time, the built area, according to the municipal ministry's regulations for construction of a domestic building, should not exceed 60% of the total site area. This standard encourages people to use the entire 60% of the site, the typical area of which is no less than 600m² on average. Reduction in the price of land for the site, along with reduction in the percentage of built area permitted, could efficiently help control and limit the building size. These measures would require a specific policy supported by stringent regulations for controlling the size of buildings.

- ***Shading devices:*** one of the most important principles of architectural design in hot climates is the use of shading devices in order to reduce the overall energy demands of the house (Farrar, 2000, Kim et al., 2012, Kischkoweit-Lopin, 2002, Li and Wong, 2007, Udagawa, 2007, Chan, 2012). In the properties analysed, no shading devices were noted; the evidence of this is in the official site plans. This absence of shading systems reduces internal thermal comfort levels, requiring the employment of additional energy consuming devices to cool the internal atmosphere to a level that is satisfactory to the occupants. Many shading techniques could usefully be applied to the buildings investigated in the case study in order to cool their internal environment, thereby reducing energy demands. External shading is also more effective than any form of internal shading system, since these internal devices absorb solar heat and radiate it to the interior.
- ***Landscaping***: Altering the area around the building would also play a major role in reducing energy demands inside the building. According to the official plans for the properties considered in this study, there is no deliberate attempt at landscaping, with one exception. The presence of trees in the external landscape can be helpful in providing shading and reducing the ambient temperature,

having a proven impact on the levels of cooling energy required within buildings (Akbari et al., 1997, Nikoofard et al., 2011, Simpson and McPherson, 1998).

- ***Onsite renewable energy***: It is widely established that on-site renewable energy can reduce energy consumption through the use of natural resources (Eroglu et al., 2011, Castillo-Cagigal et al., 2011, Omer et al., 2003). The choice of renewable technology is influenced by the level of availability of location dependent natural factors such as solar radiation, wind, etc. The kingdom of Saudi Arabia is renowned for its rich potential in natural energy resources, such as solar energy (Hepbasli and Alsuhaibani, 2011). In fact, the use of solar energy could meet a major part of the country's energy demand, while enabling Saudi Arabia to become a leading producer and exporter of solar energy in the form of electricity (Hepbasli and Alsuhaibani, 2011). This study reveals a lack of awareness and adoption of renewable energy systems in the domestic sector in Jeddah city. According to Rehman et al. the available solar radiation in the Jeddah region is about 2180 kWh/m² per year (Rehman et al., 2007),. This figure represents an abundant natural resource that would be beneficial if utilised as an alternative to fossil fuels. Since up to 15% of solar radiation can be generated as electricity(Pavlović et al., 2013), it was estimated that 2180 kWh/m² per year of solar radiation could potentially provide up to 327kWh/m² per year. This process would require the deployment of onsite renewable energy technologies such as PV panels across the domestic building stock. Provision of domestic hot water can consume up to 22% of the energy used in a dwelling, as indicated in the IES-VE simulation result for house (C). One of the most common solar collectors for hot water is the flat plate collector in the shape of a rectangular box that can be installed on top of the building (Pillai and Banerjee, 2007). The solar collectors on the tank absorb the solar radiation and heat up the water. This system is presently not used in Saudi Arabia.

- ***Bad Habits:*** Analysis of the houses and flats revealed that in addition to predicted use, the habitual behaviour of the occupants has in part led to excess fuel consumption. One example can be seen in the annual energy consumption according to the official bills in flat (C), when compared with the annual energy consumption in flat (A) or flat (B). The size of all the flats is approximately the same, and that of two of the flats is exactly the same because these flats are located on the first floor in the same building. The number of occupants for all the flats is from five to nine people but the behaviour of the occupants has led to different energy consumption results, according to the official electricity bills compared with the final simulated result. The behaviour of the occupants plays a major role in controlling the energy consumption in the house; public awareness can also play a key role in altering such behaviour.

#### *5.2.5.3 Uncertainty and risk analysis*

Uncertainty sources for energy modelling in Saudi Arabia can present positive and/or negative implications, depending on a number of sensitive factors, including the climate, available and used energy sources, and occupants' behaviour. Hence, uncertainty sources and potential risk analysis will be discussed from these three main perspectives, i.e. uncertainty of climate variation, uncertainty of natural resources, and uncertainty of energy related occupants' behaviour.

- ***Uncertainty of climate variation in Saudi Arabia:*** projected climate change and variations can have energy positive or negative implications. Saudi Arabia has a hot climate and the evidence points to rising temperatures in the future. According to Almazroui and Islam et al 2012, the rate of increase in temperature in Saudi Arabia per decade is between 0.63 °C (min) and 0.80°C (max) with a 0.72°C mean value , as obtained from the observed station datasets (Almazroui et al., 2012). However, by 2050 the temperature will increase within a range of 2.0 to 2.75° (Ragab and Prudhomme, 2000; Almazroui and Islam et al 2012 (Almazroui et al., 2012). The capacity of building adaptability for future change is hence critical (Almazroui et al., 2012). This finding illustrates a negative implication in terms of potential risk in terms of increase in energy demand, resulting in higher $CO_2$ emission rates for existing buildings in the future. The analysis of energy demand in this study was based on a weather profile provided by IES-VE in Jeddah. This does not factor in projected future climate changes.
- ***Uncertainty of natural energy sources in Saudi Arabia:*** As mentioned earlier, the temperature in Saudi Arabia may increase in the coming decades, which may also result in a positive implication in terms of increase in solar radiation. The estimation of solar energy in this study was based on the IES-VE weather profile records for Jeddah (taken hourly through the year). These records of solar radiation are in line with some previously published studies which recorded

solar radiation for Saudi Arabia, including the Jeddah region (Rehman et al., 2007). Moreover, Saudi Arabia can produce and export solar energy in the form of electricity based on its geography and location features, including widespread desert and year-round clear skies (Hepbasli and Alsuhaibani, 2011). Uncertainty of the price of fossil fuel may be interpreted as a consequence of the increasing adoption of renewable energy systems. On-site renewable energy systems such as PV can promote energy autonomy and contribute to a more stable pricing model.

- ***Uncertainty of occupants' behaviour:*** Occupant behaviour varies over time. As noted, a user profile has been established via interview with occupants, but these recorded patterns can change over time, an evolution which would be reflected in energy consumption. Behaviour can reduce or increase the energy demand.

### 5.2.6 Solutions For The Problems Faced At The Case Study Locations

Significant challenges must be addressed and overcome in the reduction of the energy consumption in existing buildings. Given the specific weaknesses that have been discovered in the houses and flats analysed by this study, there is scope for multiple solutions that could potentially reduce energy consumption; unfortunately, the adoption of some of these solutions is not possible within the context of pre-existing houses and flats, principally because these properties are already built. For example, it is not viable to destroy or remove external walls, roofs and floors in order to construct an efficient insulated house envelope. However, certain possible solutions are available to reduce energy consumption at these properties or similar structures. These possible solutions include: installing onsite renewable energy systems, installing shading devices, and replacing single glazing with more efficient double or triple glazing.

It is important to ascertain the exact annual reduction in energy consumption (kWh / m²) that could be realised using the above techniques. Therefore, the houses and flats examined by this investigation will be modelled again, based on each of these solutions. The new simulation results will be compared with the previous results in terms of annual energy consumption according to kWh / m² for each house and flat. The modification of these houses and flats will be as follows:

#### *5.2.6.1 Installing onsite energy generation (PV) systems*

The driving objective of the proposed energy generation solution is to exploit solar energy to produce electricity. Our decision not to invest in solar panels for hot water production is motivated by the practical need to minimize retrofitting costs that will be incurred by replacing the existing hot water production system widely used in Saudi Arabia. In fact, while each room has its own “window” or “split” air conditioning system that is operated using electricity, the hot water production system relies on bathroom / kitchen dedicated boilers that also use electricity. Hence, each property involves multiple boilers for hot water production.

The electricity that will be generated through PV will therefore contribute towards both air conditioning and domestic hot water energy demand (exploiting the current hot water production installation and therefore reducing retrofitting costs). In any case, it is worth noting that the generated electricity will not meet 100% of each property’s energy demand. As noted, 2180 kWh / m² per annum of solar radiation is available in the Jeddah region (Rehman et al., 2007). The installation of onsite PV will generate up to 15% of the electricity derived from solar radiation. Based on the assumption that only 30% of the roof area of each house and flat will be allocated to PV, the actual area of panelling is as follows: 45 m² for houses (A) and (B) and 117 m² for house (C). As the flats share the same roof, 30 m² of PV panels will be allocated for each flat.

The generated electricity through PV depends on the hourly solar radiation during the year. This has been calculated by IES-VE to provide an accurate account of generated electricity based on (a) the allocated roof area for PV for each property, and (b) the hourly solar radiation profile records through the year. The simulation results indicate that 8016 kWh/ per annum electricity will be generated for houses (A) and (B) and 20842 kWh/ per annum for house (C). These figures meet about 12 % of electricity demand for house (A), 24% of electricity demand for house (B), and 24% for house (C), when compared with the utility electricity bills for each property. PV will also generate about 5344 kWh/ per annum for each flat; which will contribute towards 21% of energy demand for flat (A), 19% for flat (B) and 14% for flat (C), compared with the utility electricity.

#### *5.2.6.2 Installing Shading devices*

The introduction of an external shading device to offer shade to the buildings has been recommended for these houses and flats, based upon the belief that efficient landscaping around the building area will reduce the energy required for cooling purposes especially in the case of houses.

In this case, external shutters for external windows with a resistance of 2.5 m²k/ W will be added for each house and flat. As Jeddah city is located close to the equator, the sun will be in a vertical position by the afternoon, meaning that the decision has been made to add canopies to each house and flat in order to create additional shade for the building. Additional shading devices with a height of 8 m will be added to the top of the boundary walls in order to create shade around the building, thereby cooling the immediate external environment.

#### *5.2.6.3 Replacing the single windows with efficient insulated glazing*

The single glazing currently in place can be replaced relatively simply with more efficient insulated double or triple glazing, which will have the effect of preventing the effect of the direct heat of the sun; further shading devices could also be introduced around the windows. However, the intention involved in this step is to replace the single glazing in all the houses and flats to triple insulated efficient glazing, incorporating a cavity between each pane filled with argon gas. The R-value of this new glazing will be 0.6 m²k /W.

### 5.2.7 Validation Of The Retrofitting Solutions: Simulation Results Of The Modified Models

The IES-VE simulation results based on the models developed for these houses and flats is illustrated in Figure 5.21. These results are based on the above modifications, representing the reduced annual energy reduction in terms of kWh / m² for each house and flat. The results compared with the previous IES-VE simulation results, for these houses and flats illustrate that the potential annual energy consumption reduction will be in the range of 21% to 37% for each property. As these properties are already built, this is the maximum possible realistic reduction that can be achieved in these residences in the hot and humid climate in Jeddah city.

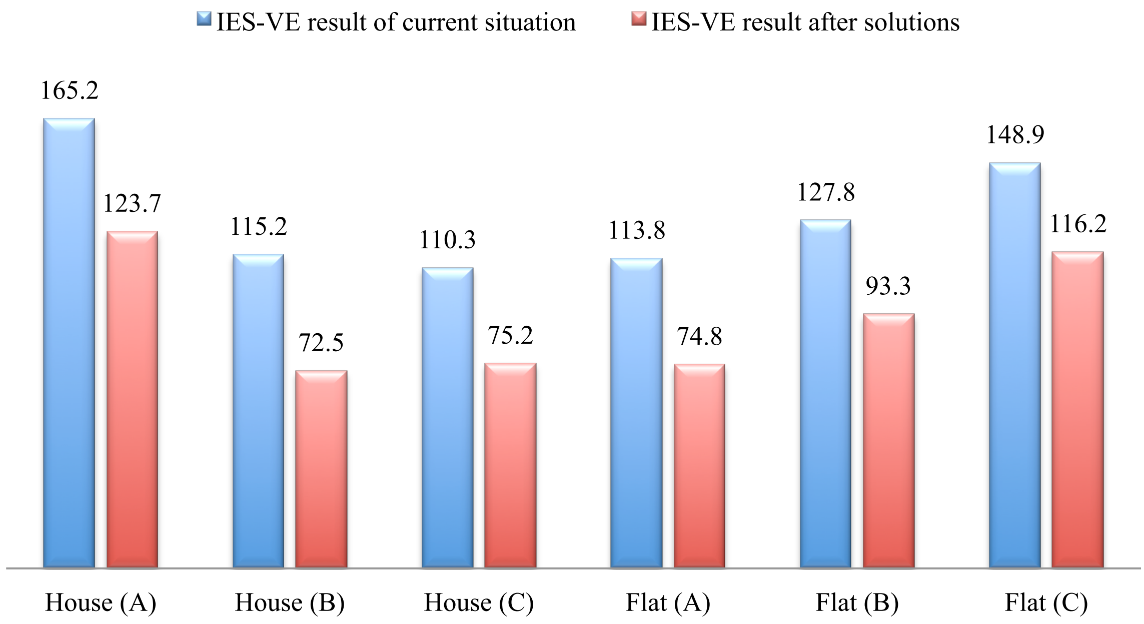



**Figure 5.21 Comparison Of Annual Energy Consumption (kWh / m²) Between The Current Situation And After Retrofitting**

In addition, it is important to consider that increasing the area of PV panels will also increase the level of energy generation. In this study, only 30% of the roof area has been allocated for the PV system at each house, while the remainder of the area has been left clear for other activities. While this is generally acceptable for existing properties, this also reflects that a more pronounced reduction in energy consumption could be achieved by the modification of similar houses and flats in the design or construction stage. Effectively this means that new residential buildings that are currently in the design stage are more likely to achieve good levels of low carbon energy building and be better suited to this hot and humid climate.

## 5.3 Hot And Arid Climate: City Of Riyadh

The city of Riyadh was chosen for this case study as it has a suitable climate and public architectural records are readily available. Table 5.7 presents the monthly average temperature and humidity levels in the city:

**Table 5.7 Riyadh City Climate Data (CDOS, 2008)**

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Max. Temperature** | 28 | 31 | 37.8 | 39.6 | 44.5 | 45.6 | 46.8 | 46 | 45 | 38 | 30.4 | 27 |
| **Min. Temperature** | -5 | -0.7 | 7 | 14 | 18.9 | 22.7 | 24.4 | 23 | 21.8 | 16.6 | 10.7 | -1.2 |
| **Relative humidity** | 44 | 25 | 13 | 19 | 15 | 9 | 10 | 12 | 16 | 26 | 49 | 34 |

The six selected study properties and the occupant user profiles are described below.

### 5.3.1 Description Of The Houses

As the average Saudi family consists of over 6 people (CDOS, 2008), the houses were expected to represent the biggest challenge. The selection of the houses was determined on the basis that each should contain an average family of not less than 6 people. All three houses are modern buildings, from 3 to 5 years old. Table 5.8 provides details of each house:

**Table 5.8 Description Of The Selected Houses**

| Property | Number of floors | Total built Area / m² | Number of Occupants |
|---|---|---|---|
| **House (A)** | 3 Floors | 699 | 6 adults 3 children |
| **House (B)** | 3 Floors | 418 | 4 adults 3 children |
| **House (C)** | 3 Floors | 418 | 3 adults 3 children |

House (A), located in the north of the city, is the largest of the three. There are two main entrances, one for men and another private entrance for women. On the ground floor this typical house contains two guest rooms for men, with private facilities, one private guest room for women, with facilities, a kitchen, and a lounge. The first floor comprises one master bedroom and five other bedrooms, all including facilities, one lounge and one sitting area (Figure 5.22). The second floor has one bedroom for the housekeeper, a laundry room, and one toilet, covering a total of less than 30% of the built area.

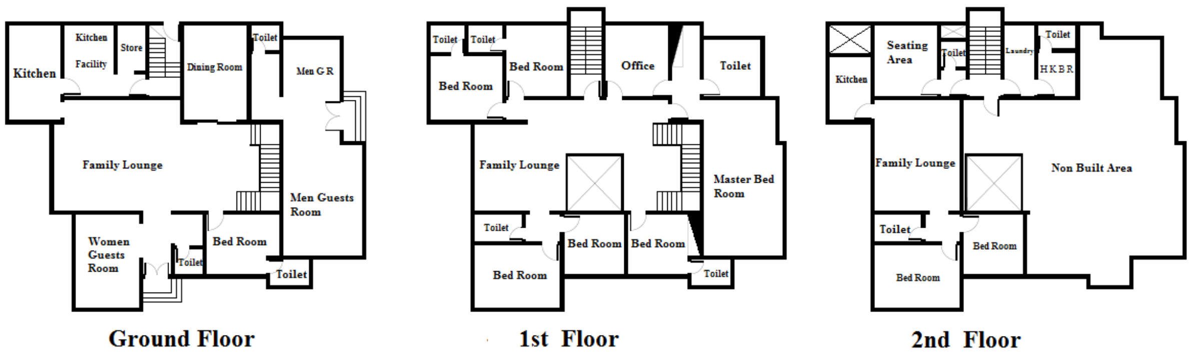



Figure 5.22 Floor Plan Of House (A)

Houses (B) and (C), are adjoined and share the same architectural design (Figure 5.23). This style of design is common in Saudi Arabia and reflects Saudi Muslim culture. The third floor of each is not completely built because the regulations for houses in Saudi Arabia only allow the construction of two floors with a few rooms on the third floor not exceeding 30% of the total built area.

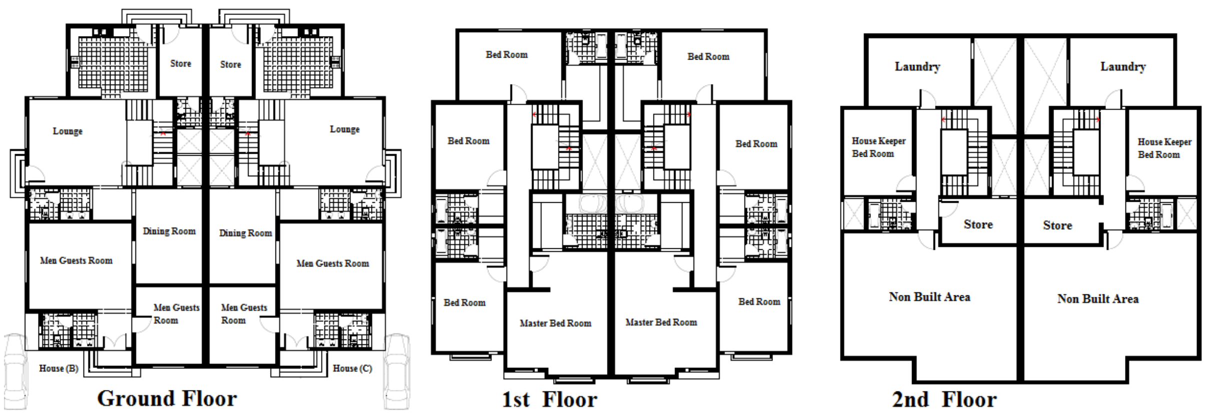



Figure 5.23 Floor Plan Of Houses (B) And (C)

The construction materials used for the building fabric in houses (B) and (C) differ from the materials used in house (A). Table 5.9 details the construction materials, according to the official construction plans for house (A), while Table 5.10 presents the construction materials used in houses (B) and (C).

**Table 5.9 Building Fabrics For House (A)**

| Element | Description | Thickness /cm | R-value $m^2k/W$ | Thermal Mass $KJ/ m^2k$ |
|---|---|---|---|---|
| **Elevation External Wall** | Rock-Mortar- red brick-mortar | 28 | 0.56 | 136 |
| **Internal Partitions** | Mortar- normal brick-mortar | 25 | 0.26 | 172 |
| **Roof** | 5 layers (tiles, mortar, sand, insulation, reinforced concrete) | 39 | 0.20 | 119.9 |
| **Floor** | 5 layers (ceramic, mortar, sand, insulation, concrete,) | 57 | 0.33 | 187.7 |
| **Windows** | Single glazing | 1 | 0.18 | --- |
| **Doors** | Wooden door | 5 | 0.2 | 22.7 |

**Table 5.10 Building Fabric For House (B) And (C)**

| Element | Description | Thickness /cm | R-value $m^2k/W$ | Thermal Mass $KJ/ m^2k$ |
|---|---|---|---|---|
| External Wall | Mortar- red brick-mortar | 25 | 0.58 | 136 |
| Internal Partitions | Mortar- normal brick-mortar | 25 | 0.26 | 172 |
| Roof | 5 layers (tiles, mortar, sand, insulation, reinforced concrete,) | 39 | 0.2 | 119.9 |
| Floor | 5 layers (ceramic, mortar, sand, insulation-reinforced concrete,) | 42 | 0.24 | 187.7 |
| Windows | Single glazing | 1 | 0.18 | --- |
| Doors | Wooden door | 5 | 0.2 | 22.7 |

### 5.3.2 Description Of The Flats

The selected flats are smaller than the houses; whilst their architectural configuration is similar to those of the houses (in terms of privacy), the room sizes differ. The flats are located in one apartment building in Riyadh. Table 5.11 details the respective floor areas and the number of household members for each flat.

**Table 5.11 Description Of The Selected Flats**

| Property | Location in the Building | Total Area m² | Number of occupants |
|---|---|---|---|
| **Flat (A)** | First Floor | 77.1 | 3 adults 2 children |
| **Flat (B)** | First Floor | 64 | 2 adults and 2 children |
| **Flat (C)** | First Floor | 94 | 4 adults and 2 children |

Each flat can contain one, two or three bedrooms including facilities. On the other hand, some flats must contain guest rooms, as do houses. The details of the architectural design of each flat selected is presented in the figure below (Figure 5.24)


**Figure 5.24 Floor Plan Of Flats (A), (B) And (C)**

The building fabric, according to the official construction plans, of the apartment building in which these flats are located is detailed in Table 5.12.

**Table 5.12 Building Fabric For Flats (A), (B) And (C)**

| Element | Description | Thickness /cm | R-value $m^2k/W$ | Thermal Mass KJ/ $m^2k$ |
|---|---|---|---|---|
| External Wall | Mortar- normal hollow concrete brick-mortar | 25 | 0.26 | 136 |
| Internal Partitions | Mortar-brick-mortar | 25 | 0.26 | 115 |
| Roof | 7 layers (Tiles, mortar, sand, mortar, insulation, silicon and concrete ) | 37 | 0.325 | 190 |
| Floor | 7 layers (Tiles, mortar, sand, reinforced concrete, insulation, concrete and basement stone) | 42 | 0.329 | 156 |
| Windows | Single glazing | 1 | 0.18 | --- |
| Doors | Wooden door | 4 | 0.2 | 35 |

### 5.3.3 Occupant User Profiles

Room usage was discussed during the interviews with the individual household to establish a particular user profile for each property. The resulting user profiles were revealed to be quite different, with the occupants in house (A) using their property very differently from those in house (B). This is perhaps attributable to the differences in age between the occupants of the two houses as well as the additional rooms in house (A) and differences of areas of each room. The interviews revealed different usage occupancy of rooms (duration and equipments). These user profiles depend on the activity of the house members and living style.

It is a typical characteristic of all the houses and flats that the bedrooms are slept in during the night and empty while the occupants are working or at school in the day. All the flats have the same rooms as bedrooms. Generally there are some common uses of other rooms, such as the sitting area, but the duration for which these are used differs from one family to another.

In this case, it is important to clarify that the behaviour of household members is one of the most important factors affecting energy consumption, reflected in their non-environmental social habits and behaviour as evidenced later in the study.

### 5.3.4 Analysis And Results

The energy consumption was simulated and analysed using IES-VE. The results of the simulations for each property were evaluated according to the design of each of the case study premises, including the building fabric used and individual user profiles. The simulations provided energy consumption and individual $CO_2$ emissions for each house and each flat. These energy consumption data were then compared with the actual energy consumption detailed on the utility bills for 2011, and analysed according to houses, flats and $CO_2$ emissions for types of dwellings. The analyses were then divided into three categories: annual energy consumption, monthly energy consumption and analysis of $CO_2$ emissions for both houses and flats.

#### *5.3.4.1 Annual Energy Consumption for houses and flats*

The average annual electrical energy consumption (kWh/m²) for the six properties studied and simulated is illustrated in Figure 5.25. Of the houses analysed, energy consumption differs from one house to another, and the average annual electrical energy consumption was found to be up to163 kWh/m². It is important to note that low energy consumption in houses does not necessarily reflect a low total energy consumption; for example, in some rooms in house (A) the energy consumption can reach up to 250 kWh/m².

House (A) has the highest level of total energy consumption according to the annual utility bills, which may in part be due to its large size. In general the actual energy consumption and the simulated results for each property prove to be approximately the same.

Analysis of the data from the flats revealed that differences in the annual energy consumption between properties were due to the uses by the occupants in each room individually. The energy consumption recorded per m² does not necessarily reflect the highest total consumption of the property, as this depends on the total covered area, but can be used as a comparison or scale for future energy reduction. From Figure 5.25 it is clear that flat (A) has the highest energy consumption compared with other flats, according to both the IES-VE simulated result and the actual utility bills, with the average electricity consumption ranging up to 203 kWh/m² / year.

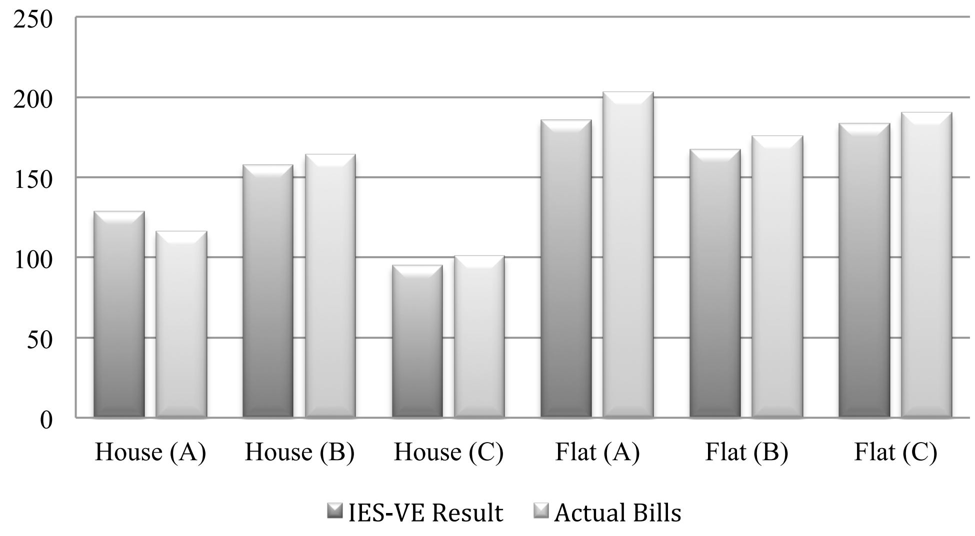



**Figure 5.25 Annual Energy Consumption (kWh/m²)**

The in-depth IES-VE analysis allowed an understanding of what the energy was consumed for in each case. As illustrated in Figure 5.26, approximately two thirds was for air-conditioning purposes. Between 64% and 71% of the energy consumed was for air conditioning needs, which may be expected due to the very hot and arid climate. A comparable result has been presented in similar previous studies (e.g. Akbari et al. 1996, cited in Taleb, 2011).

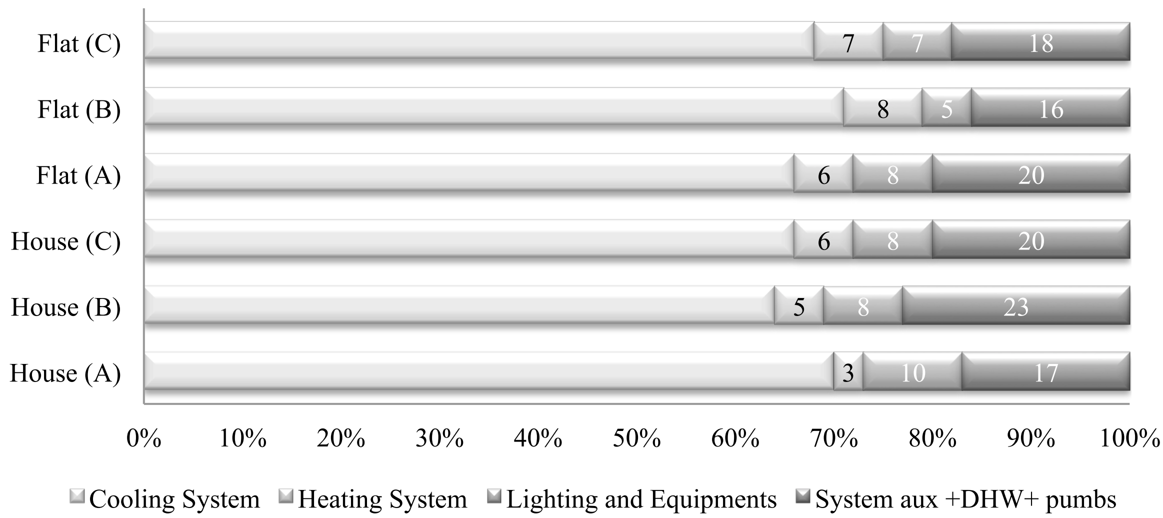



**Figure 5.26 Energy Use In Houses And Flats**

Reducing this high energy demand for air conditioning in hot, arid climates illustrates a sizeable challenge, and indicates a need to employ optimal insulation and architectural solutions. A further 15% of total energy expenditure is on pump energy and auxiliary systems, and heating for domestic hot water (DHW); therefore almost all of the problems in these houses can be presented as being either due to energy consumption issues relating to the cooling system or domestic hot water, pump energy and auxiliary systems.

The heating system, lighting and other appliances consume the least amount of energy in all cases. Indeed the heating systems are generally used only in the winter season when the temperature reaches as low as -5.0, but this season is relatively short and heating is not required during the rest of the year.

#### *5.3.4.2 Monthly Energy Consumption*

*For houses:* Figures 5.27, 5.28 and 5.29 present the monthly energy consumption data based on both IES-VE simulation results and the utility bills for 2011. For all three houses, the season with the highest level of energy consumption is the summer when the weather becomes extremely hot, necessitating a dramatic increase in the use of air conditioning facilities from May to August. Furthermore, all the occupants of the houses indicated that they often have visitors in the summer time, which also affects consumption.

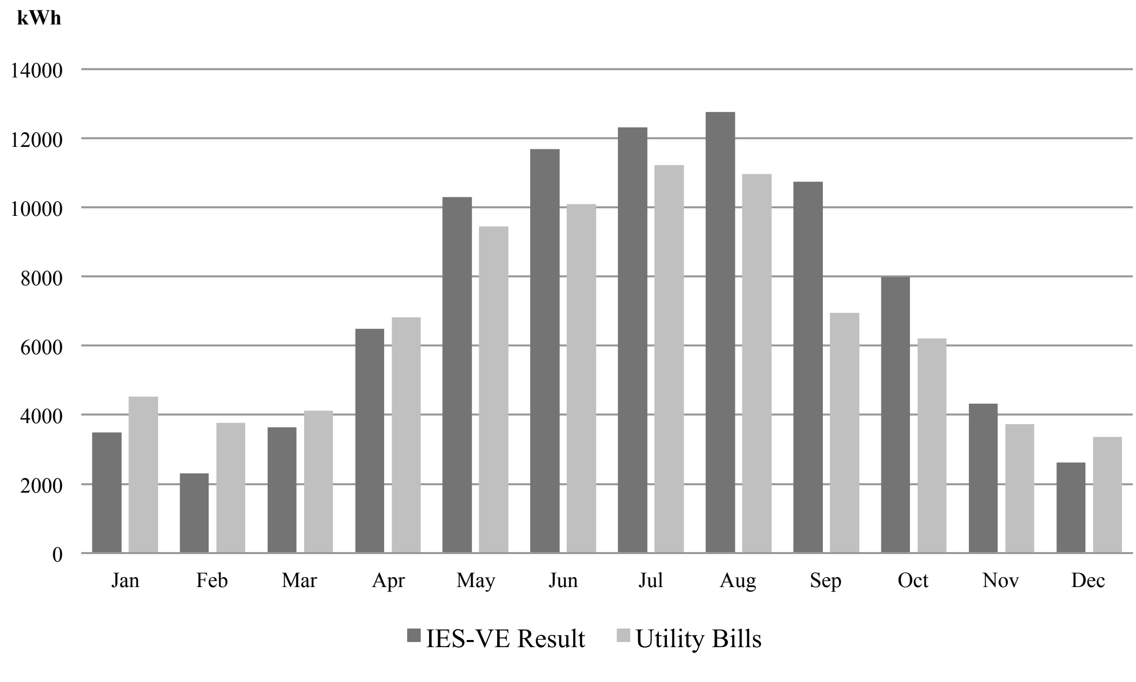



**Figure 5.27 Monthly Energy Consumption / kWh House (A)**

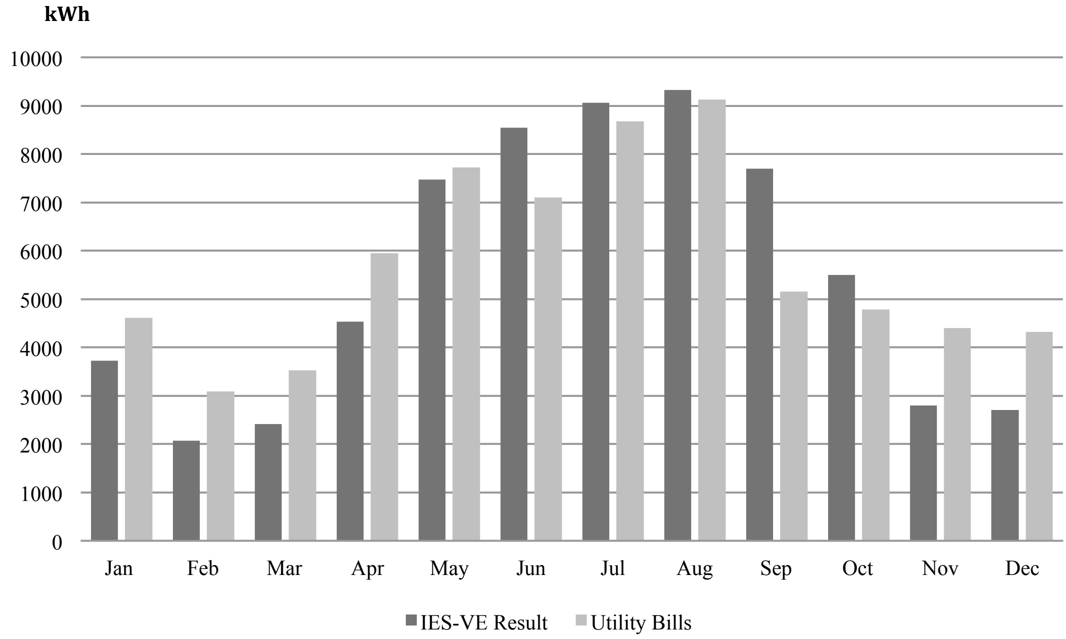



**Figure 5.28 Monthly Energy Consumption / kWh House (B)**

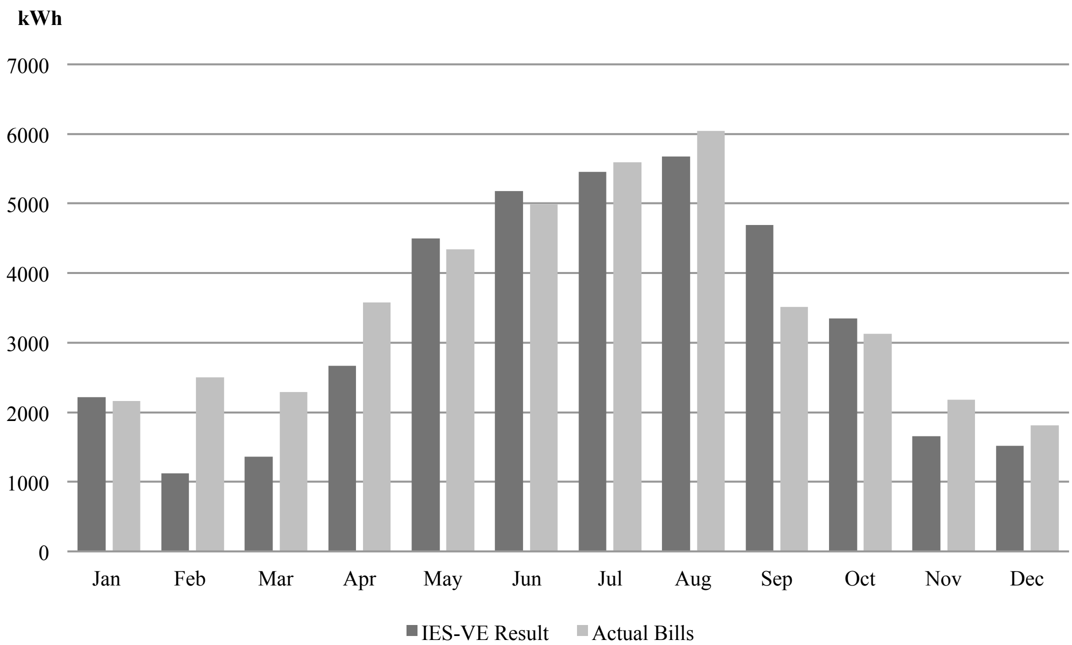



**Figure 5.29 Monthly Energy Consumption / kWh House (C)**

*For flats:* Different uses of the rooms in the property result in different energy consumption, so occupant behaviour is reflected in the energy consumption as shown in the utility bills as well as IES-VE simulation results. Figures 5.30, 5.31, and 5.32 present the monthly energy consumption according to both the utility bills and IES-VE simulation results. As mentioned previously, flat (A) has the highest level of energy consumption, with monthly energy consumption at flats (B) and (C) approximately equal throughout the year. As in the case of the houses, the highest energy consumption is during the summer period, due to the requirement for air conditioning.

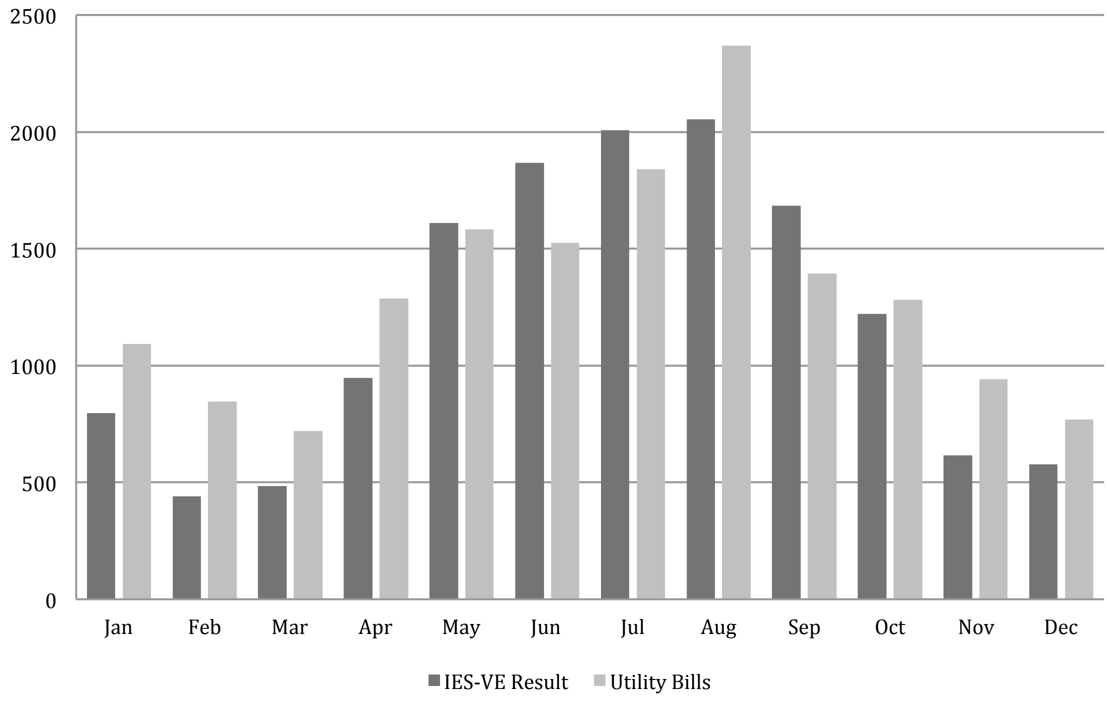



**Figure 5.30 Monthly Energy Consumption / kWh Flat (A)**

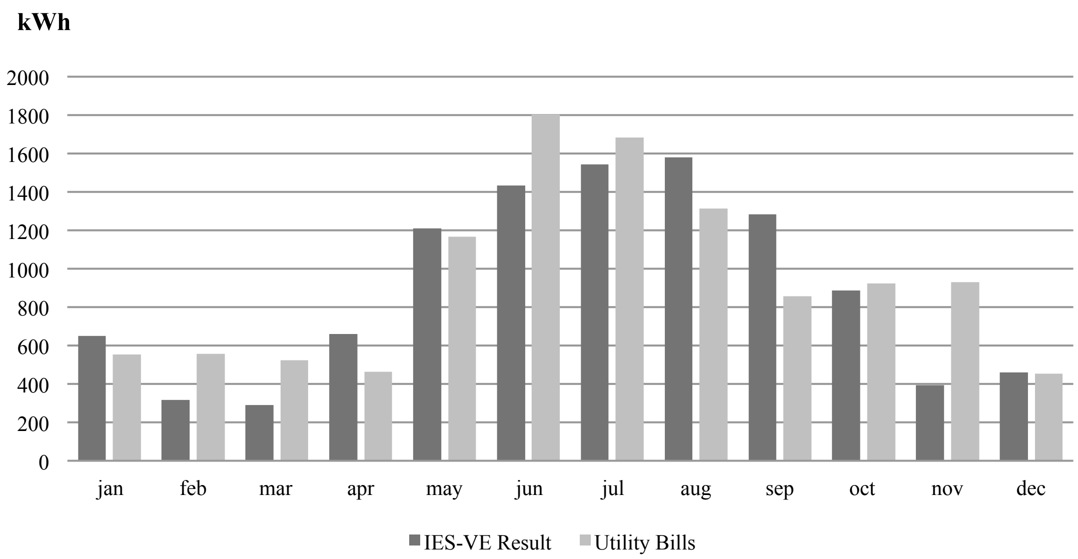



**Figure 5.31 Monthly Energy Consumption / kWh Flat (B)**

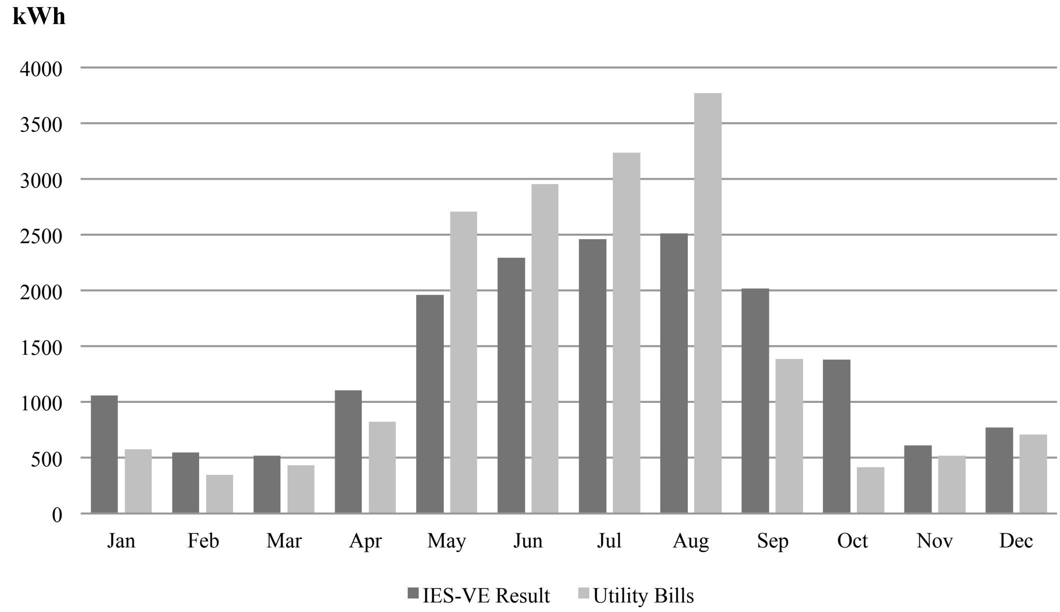



**Figure 5.32 Monthly Energy Consumption / kWh Flat (C)**

#### *5.3.4.3 $CO_2$ Emissions*

The annual $CO_2$ emission for simulated dwellings is illustrated in Figure 5.33. From an environmental perspective this figure is too high when compared to the average per capita $CO_2$ emissions in European countries. It can be seen that house (A), which is the largest property with the highest energy demand, also has the highest annual $CO_2$ emissions (42570 kg). As there are 9 household members, the annual $CO_2$ emission per capita is about 4730 kg (4.7 tons). This figure is almost double the average $CO_2$ emission per capita for the 25 EU countries (about 2.5 tons) (Doukas et al., 2006). The $CO_2$ emissions from the flats are, however, quite acceptable when compared with the noted figure for the 25 EU countries.

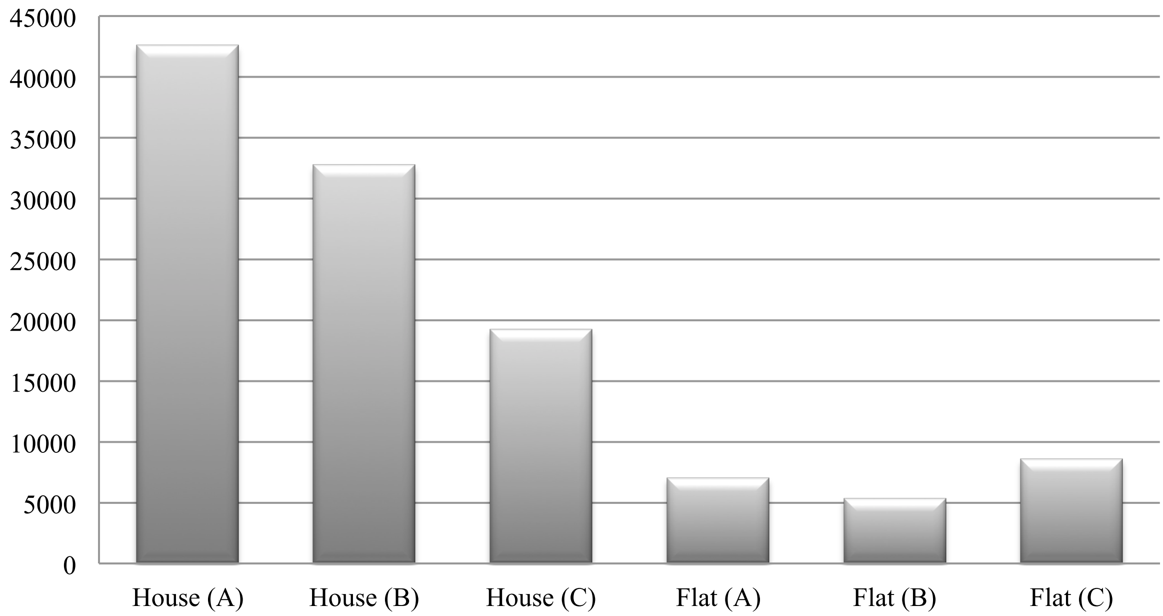



**Figure 5.33 Annual $CO_2$ Emissions (Kg) Of The Selected Properties**

In summary, analysis of the results showed that average energy consumption varies between houses and flats depending on the form, fabric and occupants' behaviour. The energy consumption for houses in the hot, arid climate of Saudi Arabia is up to 163 kWh/m² per year, while the energy consumption at a typical flat can reach to 203 kWh/m². It is important to state that this high level of energy consumption (according to kWh/m²) does not necessarily reflect the total energy consumption (kWh) of the property, as the high energy demand depends on the particular size of the property. The largest source of energy consumption is the cooling system (air conditioning), as illustrated by the data from all six properties.

### 5.3.5 Discussion

According to Blom, Itard et al. (2011), "*Energy consumption in dwellings contributes significantly to their total negative environmental impact*" (Blom et al., 2011). It is evident that according to the simulated models for the selected cases, there is high energy consumption in the domestic sector in this city, as the average annual energy consumption is up to163 kWh/m² for a typical house and up to 203 kWh/m² for a typical flat. The biggest issue causing a high demand for energy is how far occupants can control the high level of electricity consumption for cooling, especially during the summer. Lack of optimal architectural design and construction materials has been the cause of this high demand as will be described separately.

Another opportunity for potential improvement lies in the fact that approximately 15% of the energy consumed is for pump energy, auxiliary systems and to provide domestic hot water (DHW). Efficient solar gain systems may, therefore, play a key role in reducing energy demand, by heating domestic hot water in tanks located on the tops of buildings.

The analytical models for these houses and flats show high levels of $CO_2$ emissions. Given the importance of the environmental issues and the representation of these goals in legislation, this problem may be solved in future by the construction of sustainable domestic buildings.

The reasons for the high energy consumption and $CO_2$ emissions in these simulated properties are discussed below. The discussion is divided into four main categories: design weaknesses, suggested solutions that could be applicable to properties similar to those included in the case study, the simulation results after applying the suggested solutions and incentives and implementation of these findings. The suggested solutions have been simulated, and the new results compared with the current situation to identify how far these solutions are likely to be successful.

Design weaknesses within the simulated dwellings can be related to the architectural design and/or the construction materials used. These discovered weaknesses are discussed according to: architectural design (form), used construction materials (fabric), and on-site renewable energy.

#### *5.3.5.1 Architectural Design Weaknesses (Form)*

Evidence suggests that buildings should be designed in accordance with the principles of optimally sustainable architecture, in order to reduce energy demands and $CO_2$ emissions (Al-Sallal et al., 2012, Cutler et al., 2008, Radhi, 2010, Taleb and Sharples, 2011). However, the results for all six cases point to an absence of such principles in the models, with resulting high energy consumption. These architectural principles can be summarised as follows:

- ***Building size:*** extension into an area that is not needed leads to an extension of energy demand. In all of the simulated cases, the extra spaces involve the need for lighting, equipment and air-conditioning which require extra energy, resulting in additional $CO_2$ emissions. As observed from the case studies, the size of houses or flats in Saudi Arabia is influenced by the prevalent religious and socio-cultural environment, with features such as one special guest room for men and another for women. Some cultures oppose sustainability principles, a fact that is difficult to overcome when they are derived from religion.

The rooms are too big for the number of occupants of each room (e.g. the bedroom area in house (A) is about 35m² for only one or two people). This area requires cooling during the night, creating an energy demand in excess of the actual need. Furthermore, the guest rooms in house (A) are about 80m² in area. These rooms were designed to accommodate parties probably only once a month. The occupants use the rooms no more than two hours a day if they have visitors. Still, the energy that is expended in these rooms is what would be required in regularly operated spaces and does not correspond to the actual use by the occupants. Therefore it is important to note that the areas of rooms must meet the occupants' genuine needs.

- ***Building shape****:* the shape of the building can play a significant role in the reduction of energy consumption *(*AlAnzi et al., 2009*)*. As seen in all cases, each building has a flat external roof completely exposed to the sun's heat, so that rooms located on the top floor require extra energy for cooling. There is no use of natural ventilation techniques to prevent the sun from directly reaching these rooms.

- ***Natural Ventilation*****:** since wind has a major effect on induced air velocity (Yusoff et al., 2010), natural ventilation can play a significant role in cooling the internal environment or reducing the energy demand of air-conditioning used for that purpose (Hirano et al., 2006). In the analysed dwellings, ventilation techniques such as façade brace, vertical stack, or ground heat exchange are not in use. It has been noted elsewhere that ventilation has a greater effect on the interior climate than the properties of the building fabric (Kalamees et al., 2009).

- ***Shading devices techniques****:* providing shading around the building is one of the most important techniques for buildings in hot climates in terms of reducing the energy demand placed upon cooling systems (Baldinelli, 2009, Farrar, 2000). As shown in the official site plans for the case study, no shading devices are used around the selected buildings though optimal design of such devices can directly manage the sun's heat, thereby minimising the energy requirement for air-conditioning. Hence there is a significant lack of indoor thermal comfort, requiring extra energy to cool the atmosphere to the satisfaction of the occupants. There is a range of shading techniques that can be adopted in such cases. Moreover, an external shading device is much more effective than any form of internal mechanism, since the latter absorbs solar heat, which radiates to the interior during the cooling season (Baldinelli, 2009).

- ***Landscaping:*** Landscaping around the building can play a further substantial role in reducing energy demands, by providing shade and refreshing the surrounding air. According to the official plans provided for all the cases analysed in this research, only one case study, house (A), displays landscaping in its design. It is known that trees in the external landscape can be helpful in providing shade, and this has a proven impact on the levels of energy used for cooling (Akbari et al., 1997, Simpson and McPherson, 1998).

#### *5.3.5.2 Construction Materials Used (Fabric)*

***Building envelope**:* It was found that in the houses and flats analysed the R-value of the building fabric was too low. The resistance of the housing envelope is very important for preventing or slowing the passage of hot air from the outdoors to the indoors. The building fabric is one of the most important sustainable architectural features in term of energy saving (Bojic et al., 2002, Li and Chow, 2005, Lukić, 2005, Lukić, 2003), yet inadequate building fabric has been observed at the houses and flats in the study. For example, 33% to 60% of energy can be saved by using efficiently designed external walls (Balaras et al., 2007). Nearly all the dwellings analysed had the same housing envelope style, the wall layers consisting of mortar and brick and mortar, with the same lack of resistance. The exception was house (C), which contained marble in the main elevation of the building. The official construction plans and simulated models reflect the poor design of the building fabric in terms of the roofs, flooring and external walls.

The resistance (R-Value) of the house envelopes (external wall, roof and floor) was also too low: ranging from 0.2 to 0.58 $m^2k/W$ in the case of houses (B) and (C).

It was found that single glazing was used in all of the dwellings analysed, which increases the demand for electricity for air conditioning. An efficient system such as triple glazing can limit the transmission of direct-beam solar irradiation and heat from the ambient environment, while still maintaining adequate levels of daylight in the building's interior (Askar et al., 2001, Tahmasebi et al., 2011). For example, the efficient type of glazing as well as shading can improve comfort conditions by reducing the temperature of the interior (Tzempelikos et al., 2010).

***Wasteful behaviour****:* the occupants of the houses and flats analysed disclosed some behaviour that was wasteful. Generally, the use of guest rooms averages about two hours a day, while this type of room takes up a large area of the ground floor. Moreover, the annual energy consumption of house (B) is quite different to that of house (C) although this house has exactly the same design and area. The annual energy consumption according to the official bills in flat (A) is higher, compared to the annual energy consumption in flats (B) and (C). Although all of the flats have different sizes (less than 100 $m^2$), with different numbers of occupants, the behaviour of the occupants leads to different energy consumption patterns, according to both the official electricity bills and the final simulated result. Since the behaviour of occupants plays a considerable role in terms of influencing energy consumption in the homes (Virote and Neves-Silva, 2012, Hendrickson and Wittman, 2010, Romero et al., 2013), public awareness of the need to improve energy conservation behaviour should be promoted.

#### *5.3.5.3 On-site renewable energy*

Natural resources such as solar radiation can be used to generate energy instead of burning fossil fuels, thereby protecting the environment from excess $CO_2$ emissions. It is known that on-site renewable energy systems can reduce energy consumption through the use of renewable resources rather than fossil fuels to generate electricity (Castillo-Cagigal et al., 2011, Eroglu et al., 2011). This practice does, however, depend largely upon the availability and location of adequate solar radiation to meet the occupants' annual demands. In the case study analysed, there are no renewable energy systems in place (such as a PV) to generate electricity and reduce $CO_2$ emissions. According to Rehman et al. (2007), the solar radiation in Riyadh city is about 1870 kWh/$m^2$ per year.

Not utilising this constitutes squandering of a wealth of natural resources on sites and of a great opportunity to use renewable resources instead of burning fossil fuels, thus saving money and avoiding the production of excess $CO_2$ emissions. Since up to 15% of solar radiation can be generated as electricity (Pavlović et al., 2013), 1870 kWh of solar radiation may yield up to280.5 kWh/m² per year. This fact clearly calls for the use of available on-site renewable energy techniques for residential buildings.

### 5.3.6 Potential Energy Retrofitting Solutions

Despite the identified weaknesses in the selected properties, it is not realistic to sharply reduce energy consumption in properties that have already been built. For example, it is not possible to destroy external walls, roofs and floors in order to construct an efficient insulated house envelope. On the other hand, there are some practicable methods that can be employed to reduce energy consumption, including: installing on-site renewable energy systems, adding shading devices, and replacing single glazing with efficient double or triple glazing.

It is important to determine the exact potential annual reduction in energy consumption that may be attained using the above techniques. Therefore, these houses and flats were re-examined to discover what results would be achieved if each house and flat were to upgrade the glazing and install PV systems and shading devices. The new simulation results were then compared with the previous simulation results for annual energy consumption. The simulated modifications were as follows:

#### *5.3.6.1 Installing onsite energy generation (PV) system*

As noted above, about 1870 kWh/m² of annual solar radiation is available in Riyadh (Rehman et al., 2007). Installing an on-site energy generation system for each dwelling in the form of PV panels could generate up to 15% of the electricity to be derived from the sun (Pavlović et al., 2013).

In the present cases, the analysis takes into account the amount of energy to be generated through solar radiation based on allocating up to 30% of the roof area of each property to the relevant technology. By a simple calculation, the allocated PV panels for each house, covering about 30% of the roof area, would be 80m² for house (A), and 60m² for houses (B) and (C). As the flats share one building, 20m² of PV panels could be allocated to each flat.

#### *5.3.6.2 Installing Shading devices*

Installing an external shading device is another option recommended for these houses and flats, and optimal design of the landscaping around the building could most certainly reduce the energy consumed for cooling purposes, especially in the case of houses.

In this study, highly resistant (2.5 $m^2k/W$) external shutters for external windows were simulated for each property. As Riyadh city is located near the equator, the sun will be vertically overhead in the afternoon; therefore canopies would be added to each house and flat to shade the building. Moreover, some shading devices, of 7m height, were simulated on top of the boundary wall to create shading around the structure and cool the adjacent area.

#### *5.3.6.3 Replacing the single windows to an efficient insulated glazing*

The existing single glazing should be replaced with efficient insulated glazing (double or triple) to block the direct heat from the sun; further shading devices could also be introduced around the windows. In the present simulation, single glazing was replaced with efficient insulated argon filled triple glazing, in all six properties. The Thermal resistance (R-value) of this new replacement glazing is 0.6 $m^2k$ /W.

### 5.3.7 Validation Of The Retrofitting Solutions: Simulation Results Of The Modified Models

The IES-VE simulation results for the models of the modified houses and flats are shown in Figure 5.34. It may be observed from these results that the annual energy consumption is reduced from 15 % to 34% for the properties under consideration here. As these dwellings are already built, this result represents the maximum reduction that could be realistically achieved.

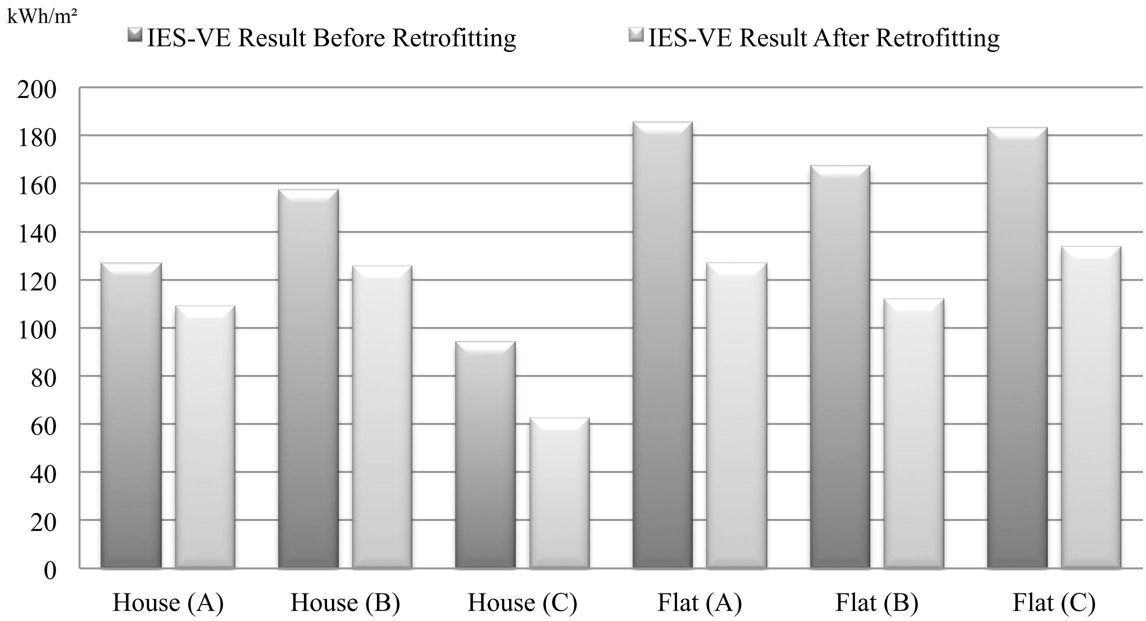



**Figure 5.34 Comparison Of Annual Energy Consumption (kWh/m²) Between The Current Situation And After Simulated Modifications**

It is important to note that only realistic limited solutions have been simulated in these dwellings; however, an increase in the area of PV panels may also lead to an increase in energy generation. In this study, about 30% of the roof area has been allocated for the PV system at each house, while the remainder of the area was left clear for other uses. Generally, this result may be acceptable for existing properties but it also indicates that a major reduction in energy consumption could be achieved if similar houses and flats were modified at the design or construction stage. New domestic buildings, currently in the design phase, are more likely to achieve satisfactorily low levels of energy consumption and carbon emissions and consequently be better suited to this climate.

### 5.3.8 Incentives And Implementation

Recent successes in the adoption of on-site renewable technology have been achieved thanks to a wide range of public financial incentives (Ruiz Romero et al., 2012). International drivers for the sustainable transformation of the energy market have in recent years spurred interest in distributed renewable energy generation across the Saudi energy value chain (Richter, 2013). Implementation of the suggested energy retrofitting solutions for existing houses and flats across Saudi Arabia will certainly require complementary measures. According to the Ministry of Electricity in Saudi Arabia, utility electricity bills sent to consumers already reduced, as the government covers about over half the price of domestic energy use. This contribution could for instance be used in a more effective way to encourage house owners to energy retrofit their dwellings, by: (a) promoting the adoption of renewable solutions, such as PV panels, rather than subsidising electricity bills; (b) highlighting potential energy savings with reduction in energy bills, while maintaining overall occupants' comfort conditions; and (c) establishing governmental directives to promote sustainable buildings in Saudi Arabia, including the development of more stringent policies and regulations that would assist in implementing and monitoring energy savings and $CO_2$ emission reduction across the country. As this study is sponsored by the Saudi Government and the ministry of municipality in Saudi Arabia, the researcher will endeavour to ensure that the results inform positively the current changing energy policy landscape in Saudi Arabia.

## 5.4 Hot And Arid Climate And High Mountainous Topography: City Of Al-Baha

Al-Baha region, located in the south-west of Saudi Arabia, has a hot, arid climate. It was chosen for this study as representative of the mountainous regions of Saudi Arabia; despite being colder than other regions of the Kingdom, it is still hot and arid compared to many other countries. The table below illustrates the typical weather conditions of this region (Table 5.13)

**Table 5.13 Weather Conditions In Al-Baha Region (CDOS, 2008)**

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Max Temperature** | 28.3 | 28.5 | 31.8 | 34 | 37 | 37 | 38 | 37 | 37.6 | 32 | 28.6 | 29 |
| **Min Temperature** | 2.4 | 3 | 9 | 16 | 16 | 19 | 21 | 20 | 19.6 | 13 | 11 | 3 |
| **Relative humidity** | 66 | 41 | 28 | 37 | 38 | 28 | 23 | 23 | 28 | 33 | 55 | 44 |

Across the region, six dwellings, three typical houses and three typical flats, have been chosen. Their descriptions will fall into three main categories: houses, flats, and user profiles of the households.

### 5.4.1 Description Of The Selected Houses

The three houses have been selected in different locations. The criteria for selection took into account the number of household members, areas, sizes and construction materials used, in order to ensure that they were typical of domestic buildings in the region. Table 5.14 presents a profile of each house.

**Table 5.14 Occupants And Description Of The Selected Houses**

| Property | Number of Floors | Total Built Area ($m^2$) | Number of Occupants |
|---|---|---|---|
| **House (A)** | 2 Floors | 549.6 | 6 Adults 4 Children |
| **House (B)** | 2 Floors | 498.8 | 5 Adults 3 Children |
| **House (C)** | 2 Floors | 530.5 | 5 Adults 2 Children |

Figure 5.35 presents the subdivision floor plans of house (A); Figure 5.36 presents the layout floor plans of house (B); and Figure 5.37 presents the layout plans of house (C).

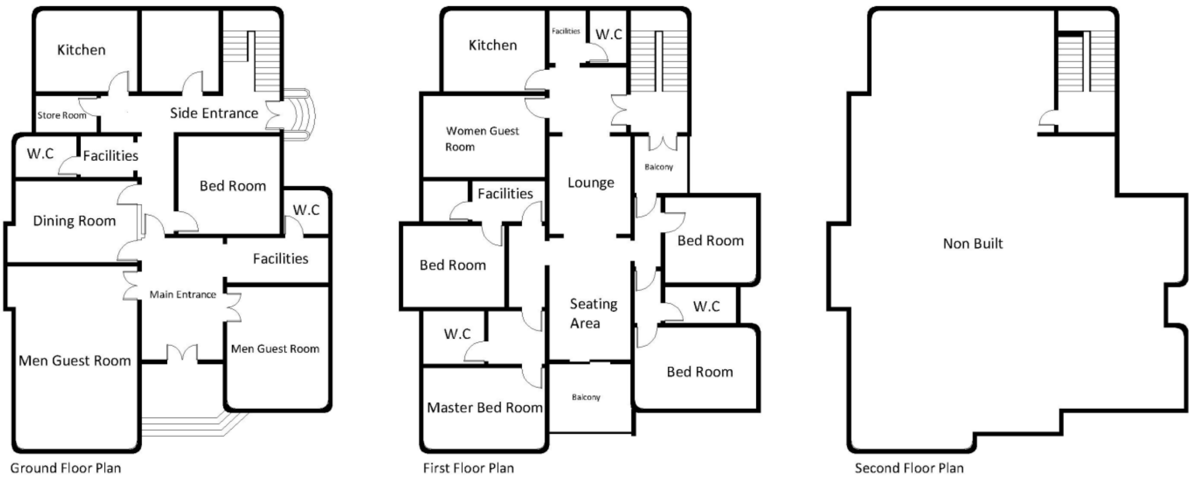



Figure 5.35 Floor Plans Of House (A)

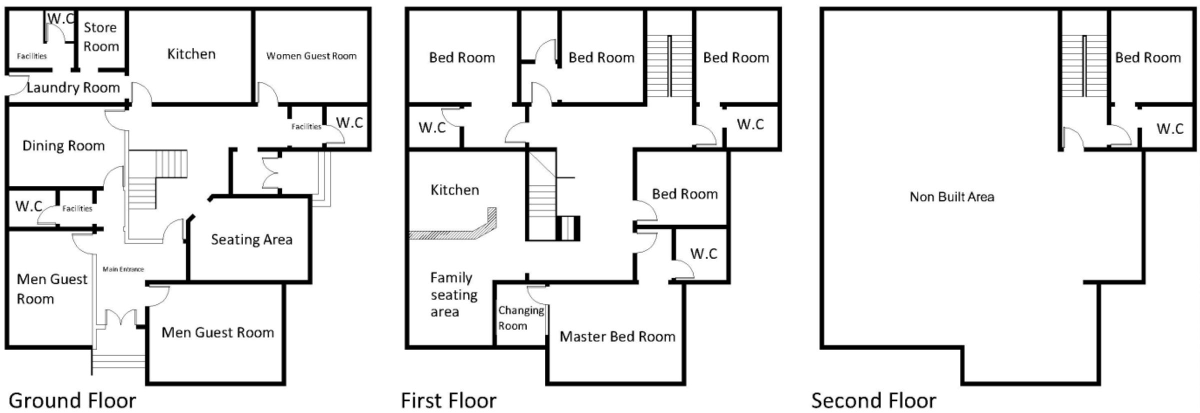



Figure 5.36 Floor Plans Of House (B)

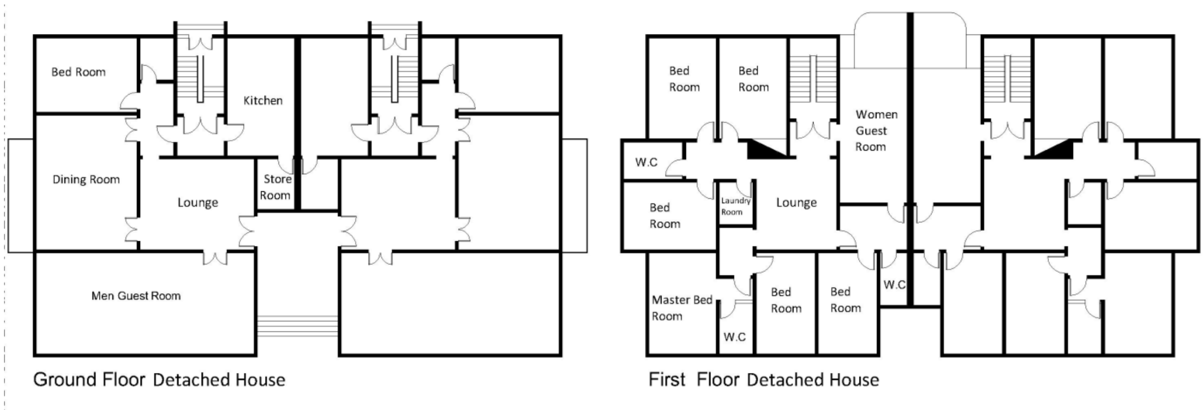



Figure 5.37 Floor Plans Of House (C)

Architecturally, these houses are typical of Saudi Arabian homes, according to the Ministry of Municipality. They all include large guest rooms and separate entrances for males and females, in accordance with local customs. Many large bedrooms and many toilets can be seen in the layout plans, which is again typical given the size of Saudi families and the presence of live-in servants.

The construction materials used for the houses are illustrated individually. Table 5.15 presents the building fabric of house (A); Table 5.16 presents the building fabric of house (B); and Table 5.17 presents the building fabric of house (C).

**Table 5.15 Building Fabric For House (A)**

| Element | Description | Thickness /cm | R-value $m^2k/W$ | Thermal Mass $KJ/m^2k$ |
|---|---|---|---|---|
| **External Wall** | 3 layers (Mortar- red brick-mortar) | 25 | 0.58 | 136 |
| **Internal Partitions** | 3 layers (Mortar- normal brick-mortar) | 25 | 0.26 | 168 |
| **Roof** | 5 layers (tiles, mortar, sand, insulation, reinforced concrete,) | 39 | 0.2 | 119.9 |
| **Floor** | 5 layers (Tile, concrete, sand, insulation- Basement concrete,) | 42 | 0.1 | 187.7 |
| **Windows** | Single glazing | 1 | 0.18 | --- |
| **Doors** | Wooden door | 5 | 0.2 | 22.7 |

**Table 5.16 Building Fabric For House (B)**

| Element | Description | Thickness /cm | R-value $m^2k/W$ | Thermal Mass $KJ/m2^2k$ |
|---|---|---|---|---|
| **External Wall** | 3 layers (Mortar- normal brick-mortar) | 25 | 0.26 | 136 |
| **Internal Partitions** | 3 layers (Mortar- normal brick-mortar) | 25 | 0.26 | 60 |
| **Roof** | 5 layers (tiles, mortar, sand, insulation, reinforced cast concrete) | 39 | 0.3 | 190 |
| **Floor** | 5 layers (Tile, mortar, concrete- Basement concrete, sand stone) | 47 | 0.2 | 173.3 |
| **Windows** | Single glazing | 1 | 0.18 | --- |
| **Doors** | Wooden door | 5 | 0.2 | 22.7 |

**Table 5.17 Building Fabric For House (C)**

| Element | Description | Thickness /cm | R-value $m^2k/W$ | Thermal Mass KJ/ $m^2k$ |
|---|---|---|---|---|
| **Main Elevation External Wall** | 4 layers (Marble-Mortar- Normal brick-mortar) | 27 | 0.55 | 136 |
| **External Wall** | 3 layers (Mortar- Normal brick-mortar) | 25 | 0.26 | 136 |
| **Internal Partitions** | 3 layers (Mortar- normal brick-mortar) | 25 | 0.26 | 172.3 |
| **Roof** | 5 layers (tiles, mortar, sand, insulation, reinforced concrete,) | 39 | 0.2 | 119.9 |
| **Floor** | 5 layers (ceramic, mortar, sand, insulation- concrete,) | 57 | 0.33 | 187.7 |
| **Windows** | Single glazing | 1 | 0.18 | --- |
| **Doors** | Wooden door | 5 | 0.2 | 22.7 |

### 5.4.2 Description Of The Selected Flats

Three typical flats were selected based upon the number of occupants, to ensure that they fell within the average range of Saudi families. These three flats are located in different floors of a three floor building in the south of the region. Table 5.18 below provides the details of each flat, including the area and the number of occupants.

**Table 5.18 Occupants and description of the selected flats**

| Property | Location in the building | Area ($m^2$) | Number of Occupants |
|---|---|---|---|
| **Flat (A)** | Third Floor | 240.7 | 4 Adults 3 Children |
| **Flat (B)** | Third Floor | 240.7 | 3 Adults 4 Children |
| **Flat (C)** | Second Floor | 240.7 | 2 Adults 3 Children |

Architecturally, each flat contains a smaller guest room than that of the houses, and two toilets, including facilities, one master bedroom and three additional smaller bedrooms. (Figure 5.38).

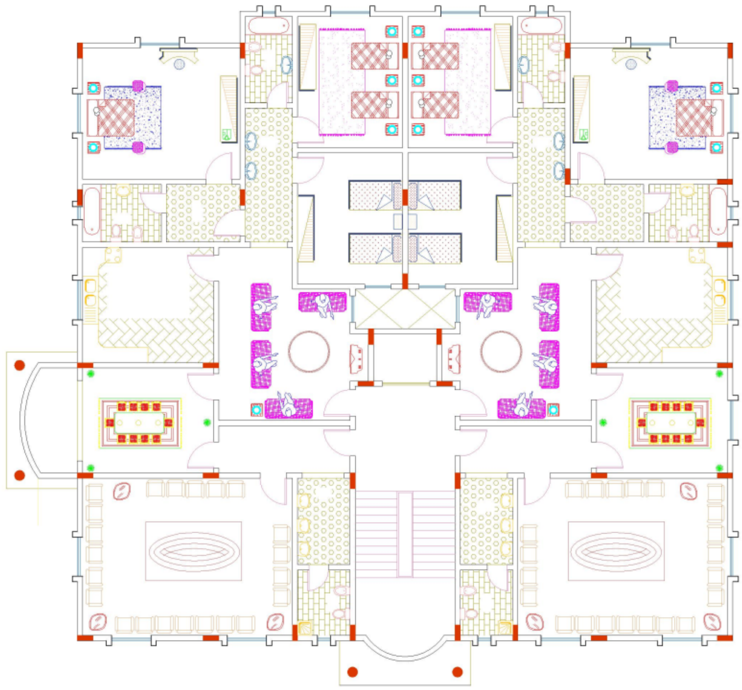


**Figure 5.38 Multiple Floor Plan Of Flats**

The construction materials used in the building envelope are illustrated in Table 5.19. A similarity can be seen between the construction materials used in the building envelope of this building and the materials used in the houses.

**Table 5.19 Building Fabric Of The Building For Flats (A), (B) And (C)**

| Element | Description | Thickness /cm | R-value $m^2k/W$ | Thermal Mass $KJ/m^2k$ |
|---|---|---|---|---|
| **External Wall** | 3 layers (Mortar- normal hollow concrete brick –mortar) | 25 | 0.26 | 136 |
| **Internal Partitions** | 3 layers (Mortar- normal brick- mortar) | 25 | 0.26 | 172 |
| **Roof** | 5 layers (tiles, mortar, insulation, sand ,reinforced concrete,) | 37 | 0.32 | 119.9 |
| **Floor** | 5 layers (ceramic, mortar, sand, insulation- reinforced concrete,) | 42 | 0.1 | 187.7 |
| **Windows** | Single glazing | 1 | 0.18 | --- |
| **Doors** | Wooden door | 5 | 0.2 | 22.7 |

### 5.4.3 Occupant User Profiles

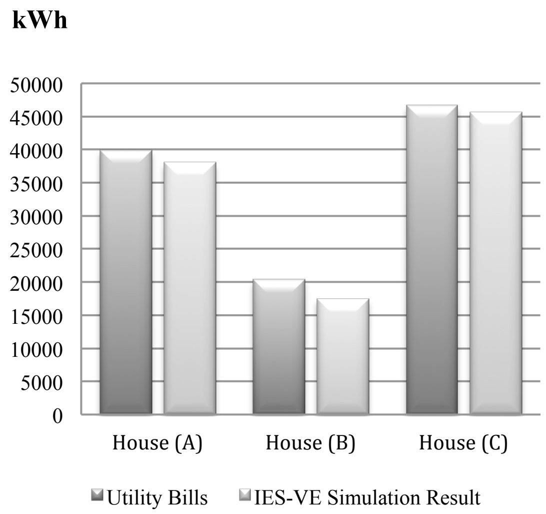
To ensure a realistic simulation, accurate data for the occupants' activities and patterns were required (Korjenic and Bednar, 2012). Individual interviews were therefore conducted with each household in order to create profiles of each occupant. The IES-VE model for each dwelling then included an individual profile for each room, incorporating: the daily period of operation; the internal temperature; and the equipment and lighting in that room. While the use of rooms differs between dwellings, certain common behaviours could be expected. For example, bedrooms are expected to be in operation from 22:00 to 07:00, because the official work day in Saudi Arabia is from 7:30 to 14:30, while the school day runs from 6:30 to 14:00. All occupants in this study have guests between 19:00 to 22:00, using their large guest rooms for this purpose. Some occupants use the bedroom for other activities, including internet use or study. Many families also continue to use lights and air-conditioning throughout the day, as electricity is relatively cheap in the Kingdom.

### 5.4.4 Analysis And Results

These houses and flats were simulated using IES-VE software tools in order to identify the annual energy consumption (usage details and $CO_2$ emission rate) of each property. To support the analysis, the IES-VE simulation results were compared with the annual energy consumption provided in the official electricity bills, which were made available by the Ministry of Electricity. For this purpose, the analyses were divided into four main categories: analysis of houses; analysis of flats; details of what the energy is being consumed for and analysis of $CO_2$ emission rate.

#### *5.4.4.1 Analysis of Houses*

The annual energy consumption for the 3 typical houses is displayed as kWh and kWh/m² in Figures 5.39 and 5.40 respectively. The energy consumption in houses in this region reaches 88 kWh/m². The annual energy consumption modelled by the IES-VE simulation corresponds closely to the energy consumption presented in the official utility bills. It is important to note that this figure describes the average energy consumption (kWh/m²) for the whole house, although the energy consumption in some rooms, such as the bedroom in house (C), can reach over 150 kWh/m². Compared to the average annual energy consumption in some developed countries, the energy consumption in these houses is high, suggesting that the problem is affected by the local climate. Additionally, low energy consumption in kWh/m² does not necessarily reflect low total energy consumption by the property; it depends on the total area of the dwelling, which is likely to include some rooms that are not often used. House (B) has the lowest energy consumption according to the official utility bills and IES-VE simulation result, because the occupants travel abroad numerous times each year so that some rooms are not in regular use.



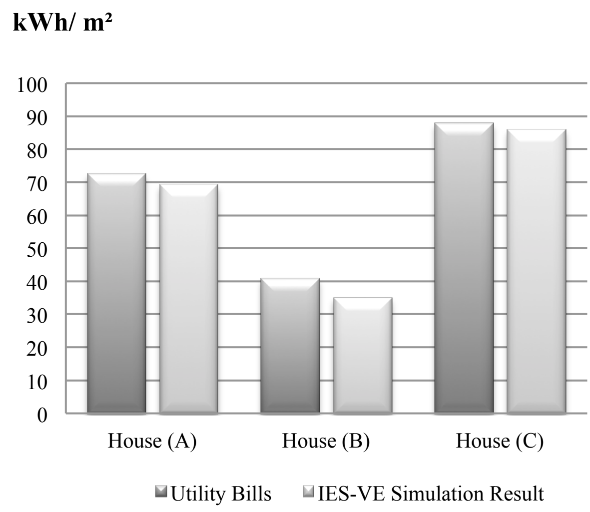




**Figure 5.39 Total Annual Energy Consumption In kWh**

**Figure 5.40 Total Annual Energy Consumption For Each House In kWh/ m²**

The Ministry of Electricity for the Al-Baha region issues electricity bills every quarter. These quarters are not strictly governed by season and therefore some bills will span periods of higher or lower usage. The seasonal energy consumption according to IES-VE will be compared with the official electricity bills provided (see Figures 5.41., 5.42 and 5.43). The annual energy consumption according to the official bills is very similar to the IES-VE simulation results. The data show that the region is especially hot during three seasons, which correlates to high energy consumption caused by continual operation of air-conditioning units. However, the official energy consumption of the houses in the summertime differs from the simulation results. This may be due to the fact that residents typically travel to other cities or countries at this time of year.

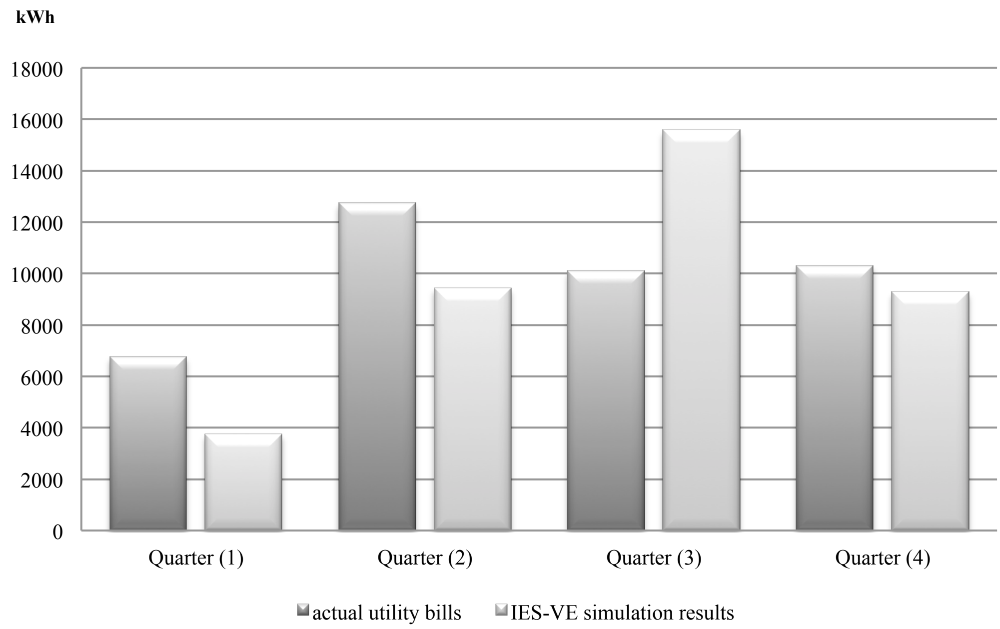



**Figure 5.41 Seasonal Energy Consumption / kWh House (A)**

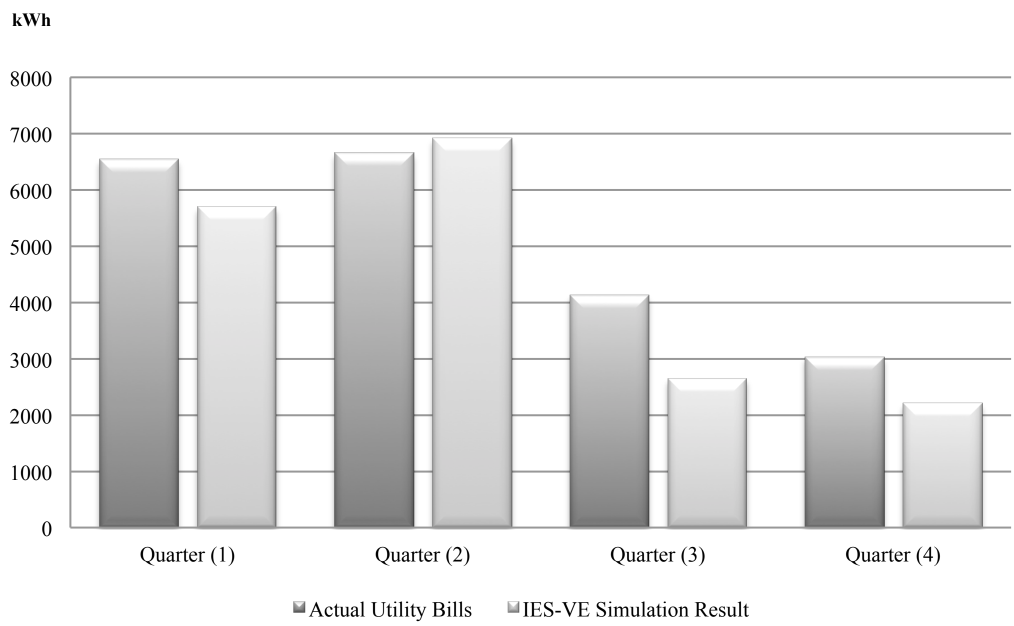



**Figure 5.42 Seasonal Energy Consumption / kWh House (B)**

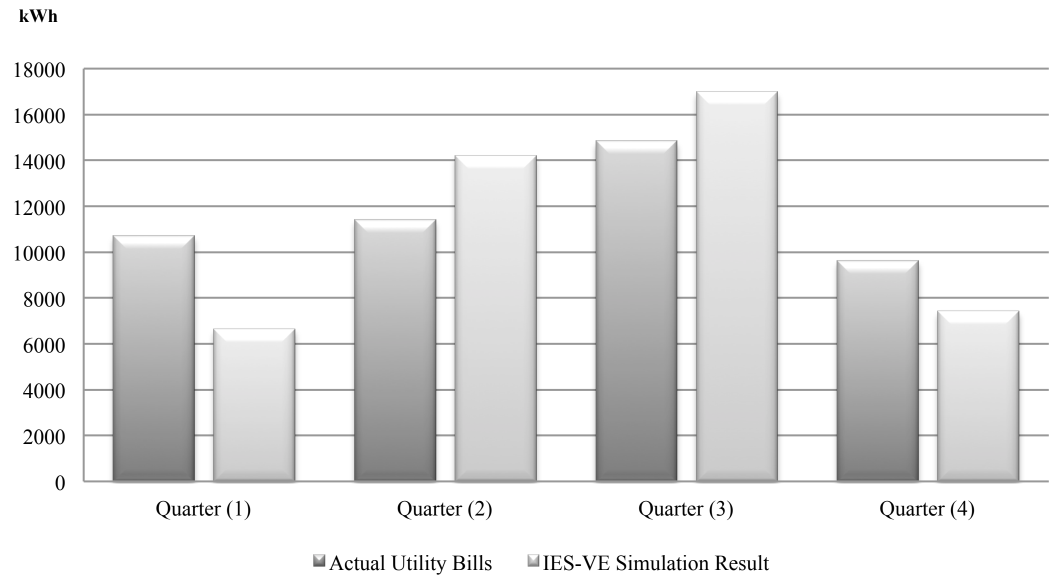
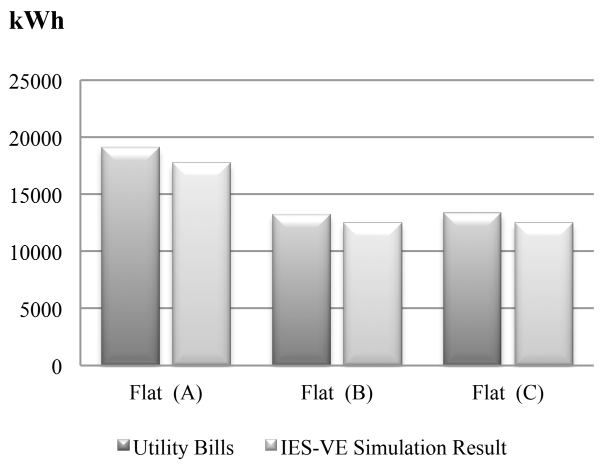



**Figure 5.43 Seasonal Energy Consumption / kWh House (C)**

### *5.4.4.2 Analysis of flats*

The average annual energy consumption in kWh/m² is lower for flats than for houses, bearing in mind that the total usage will be lower because the area is smaller. In Figures 5.44 and 5.45 below, it can be seen that the energy consumption in flats in this region can reach 79 kWh/m². The annual energy consumption data from the official bills are similar to the results of the simulation; however, the actual level of energy use differs depending on the number and profile of occupants.



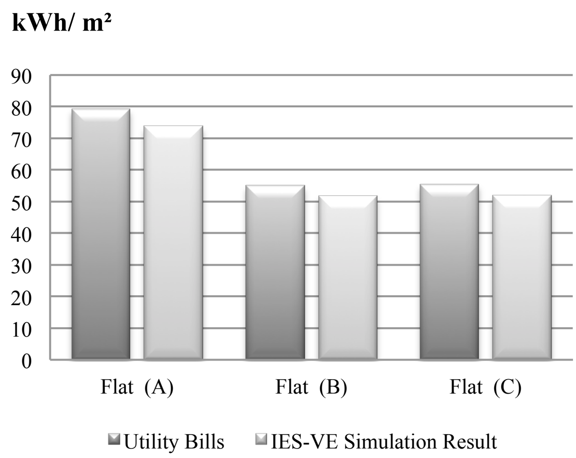




**Figure 5.44 Total Annual Energy Consumption In kWh**

**Figure 5.45 Total Annual Energy Consumption For Each Flat In /kWh/ m²**

The seasonal energy consumption of each simulated flat is provided in Figures 5.46, 5.47 and 5.48. These figures are compiled from the IES-VE simulation and official utility bills for 2011. It is clear that the hottest seasons require heavy use for the purposes of air conditioning. However, as with houses, some occupants (B) travel abroad during these seasons, as reflected in lower levels of energy use.

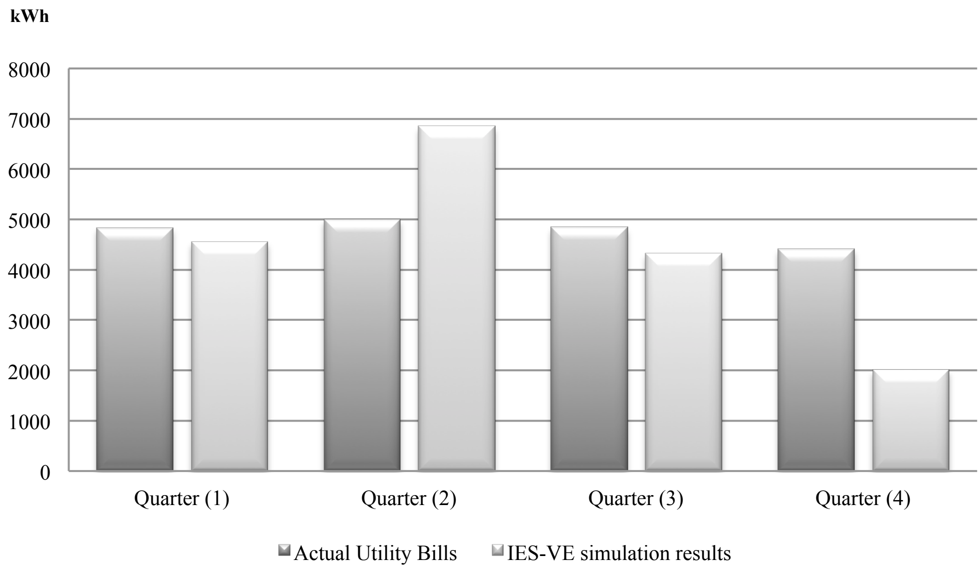



**Figure 5.46 Seasonal Energy Consumption / kWh Flat (A)**

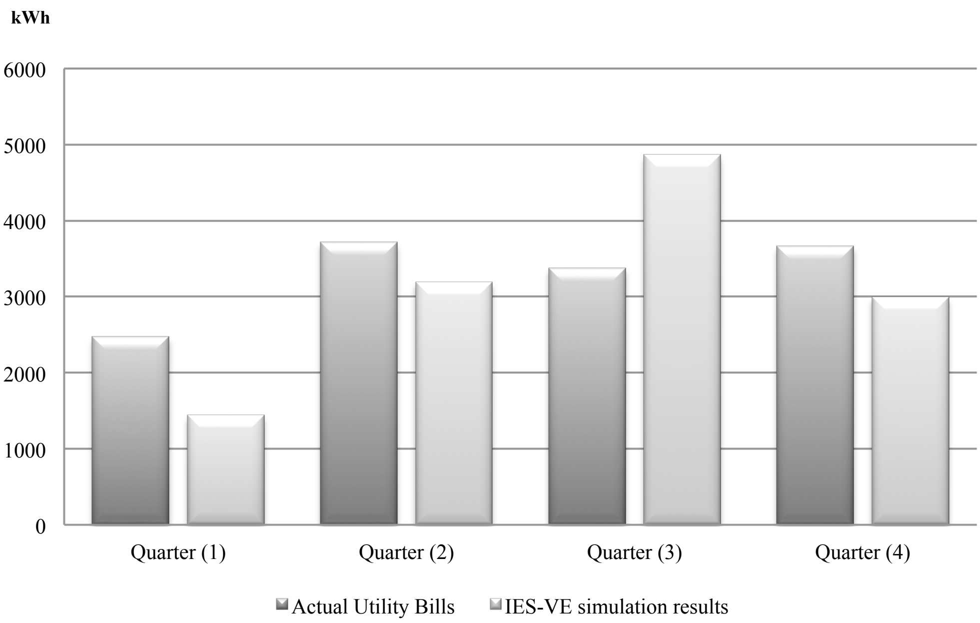



**Figure 5.47 Seasonal Energy Consumption / kWh Flat (B)**

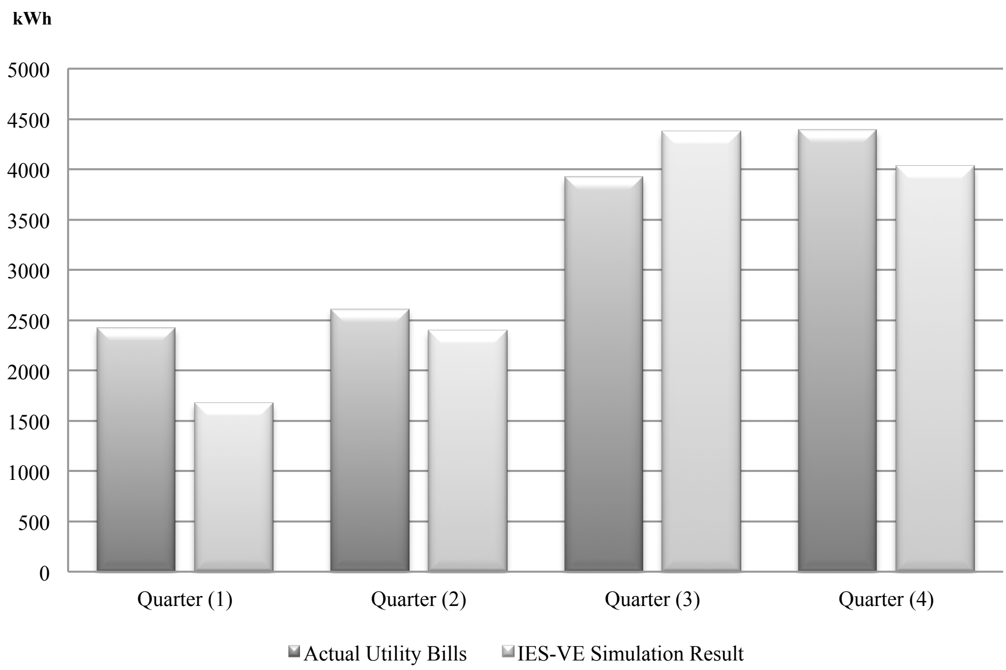



**Figure 5.48 Seasonal Energy Consumption / kWh Flat (C)**

### *5.4.4.3 Details of energy consumption for houses and flats*

The specific details of energy use in each dwelling according to the results of the IES-VE simulation are illustrated in Figure 5.49. The biggest contributor to energy consumption is air-conditioning, which uses up to 69% of the total energy consumed. The local climate in Saudi Arabia makes air-conditioning necessary to ensure human thermal comfort in the internal areas of the property. Domestic hot water (DHW), auxiliary systems and pumps energy also account for a minimum of 20% of the total energy consumption in the property. Through the use of natural solar heat, it may therefore be possible to heat the domestic water located on the top floor of the property. Lighting and other equipment are responsible for the lowest proportion of energy usage in each property. According to the simulation results, air-conditioning accounts for the bulk of the energy usage in all three of the flats. As with the houses, DHW, auxiliary systems and pumps energy cause a minimum of 18% of the total energy consumption in the property. These two issues can be dealt with technically and socially in order to reduce energy consumption and $CO_2$ emissions.

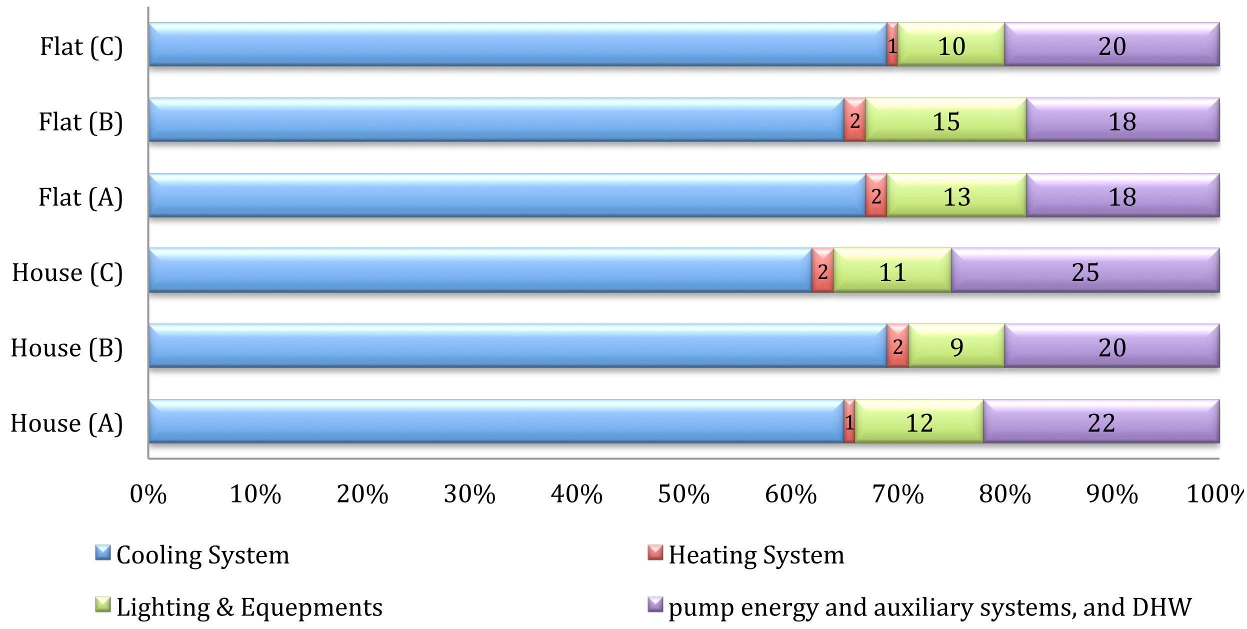



**Figure 5.49 Energy Use In Houses And Flats**

### *5.4.4.4 CO2 emission rates for the simulated dwellings*

Environmental protection is an important issue, involving the minimisation of fossil fuel burning. In Saudi Arabia, domestic buildings account for more than 50% of total energy consumption, so the use of natural resources and techniques, as well as increased public awareness, could potentially have a significant effect on national figures. For both the houses and the flats, the $CO_2$ emission rates (kg) are displayed in Figure 5.50. The annual $CO_2$ emission rate (tonnes) per capita is higher than that shown in the figures for 25 EU countries. For example, the per capita $CO_2$ emissions for House (C) are 3.3 Tons, while houses in the 25 EU countries generate about 2.5 Tons (Doukas et al., 2006). This figure suggests that Saudi Arabian architects need to take environmental issues into account in their future designs.

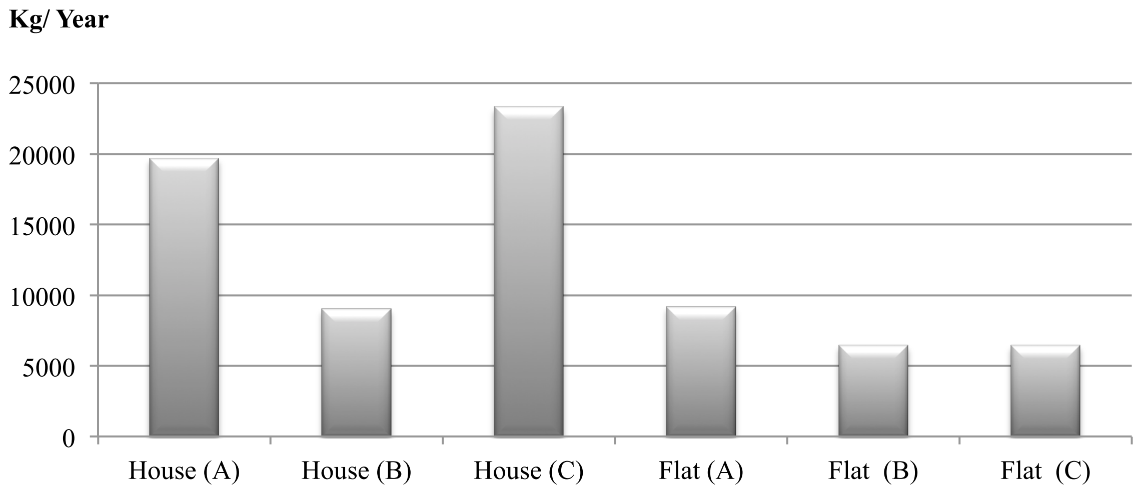



**Figure 5.50 Annual $CO_2$ Emissions (Kg)**

In summary, the average annual energy consumption in this region can reach 88 kWh/m² for houses and 79 kWh/m² for flats. The cooling system and DHW account for the largest proportion of this use. By addressing these two major weaknesses, it should be possible to reduce the energy consumption and $CO_2$ emissions, thereby helping to achieve sustainability in this region.

### 5.4.5 Discussion

In these simulated dwellings, the annual energy consumption (kWh/m²) seems to be higher than in many developed countries and in excess of the guidelines of established energy consumption codes. These energy consumption figures seem to result from poor building design (form and fabric); occupant behaviour; and the under-utilisation of on-site renewable energy. Identification of these weaknesses offers an excellent opportunity to improve existing dwellings and, particularly, the performance of future dwellings.

The weaknesses in building design and envelope (form and fabric) will be discussed separately. The discussion will be informed by the analysis of these six properties, the available building design specifications, and the behaviour of the occupants of each property. Potential solutions will be suggested for these dwellings and any similar cases. In order to determine the success of the suggested solutions, the cases will be remodelled on the basis of these solutions and re-simulated to predict potential energy savings. The new simulation results for each dwelling (after retrofitting) will be compared again with the previous simulation results (before retrofitting) in order to ascertain the success of the potential solutions.

This discussion will be divided into two main sections: the weaknesses of the analysed dwellings, and suggested solutions for these or similar cases. The weaknesses of each dwelling can be related to building design (form); building envelope (fabric); on-site renewable energy; and/or occupant behaviour. The discussion of weaknesses will be organised as follows:

- Architectural design (form)
- Building envelop (fabric)
- On-site renewable energy and occupant behaviours

#### *5.4.5.1 Architectural design weaknesses (form)*

According to Mulder, K.F (2007), "*Environmentally conscious design has been practiced in engineering design for more than a decade*" (Mulder, 2007). Many architects focus on the design stage to ensure the creation of buildings that are more economical in terms of energy consumption for cooling, heating, lighting, ventilation and the supply of hot water (Woolf, 2003). Thus, the buildings should be designed in accordance with sustainable architectural standards with regard to energy savings and minimisation of $CO_2$ emission (Cutler et al., 2008). Moreover, the standard of "Passivhaus" has been established originally for central Europe but there are recent studies that have been developed to support its application for hot environments (Tubelo et al., 2014). Architectural designs include building size, shape, shading devices and landscaping. In the dwellings selected for this study, the following weaknesses were identified:

- Building size

As seen in the construction plans of each simulated dwelling, the buildings seem to be large in comparison with the number of occupants (household members) in each property. Room sizes in all simulated dwellings are large spaces with a small number of occupants. For example, the bedrooms in house (A) occupy from 20 to 24 m², for no more than two people per room. The extra space incurs increased energy costs for air-conditioning, heating and lighting.

Electricity in Saudi Arabia is subsidised (Alyousef and Stevens, 2011), leading to higher than necessary levels of energy consumption and $CO_2$ production. Large building spaces are major contributors to this waste, and therefore it is logical to propose that properties be designed more appropriately for the needs and numbers of occupants. Increasing the price of electricity would also lead to reduction in the size of buildings, thereby controlling energy consumption.

- Building shape

Typically, buildings should be designed to conform to local environmental conditions. The design concept in all the simulated dwellings and, indeed, in most Saudi domestic buildings, is a flat shape, with the rooms at the top of the structure directly facing the sun. This results in higher energy consumption for the majority of the seasons in Saudi Arabia. The problem is exacerbated by the fact that the top floors are typically allocated to high-use rooms, such as bedrooms and lounges, which must be cooled for longer periods. Many possible solutions can be adopted within the design process for future buildings, by designing structures with techniques suitable for sloped roofing and allocation of the roof to on-site renewable energy technology, such as PV.

- Natural ventilation

Wind is known to play a major role in controlling air movement; hence natural ventilation can minimise the energy demands of air-conditioning by cooling the indoors naturally. Ventilation can also affect the interior climate more significantly than the properties of the building fabric (Kalamees et al., 2009). In this study, all the dwellings considered utilise only air conditioning for cooling, despite the fact that the natural ventilation available in a mountainous area may be more effective and more efficient for the purpose, without consuming energy or emitting $CO_2$. No efficient ventilation techniques were found in the dwellings analysed. Therefore, due consideration could be given to techniques such as solar chimneys for ventilation, façade braces and ground heat exchanges in cold seasons.

- Shading devices

Shading devices are a core architectural design principle in energy saving, with optimal design of shading devices allowing the creation of extra shadow around a building, resulting in the reduction of external temperatures (Baldinelli, 2009, Farrar, 2000). No shading device techniques were found in the dwellings in this study. As optimal design and use of shading devices can reduce energy demands, these buildings should be retrofitted accordingly.

The best possible landscape design around the building will give the property a good appearance, refresh its atmosphere and reduce the local temperature. On this basis, the design of the landscape according to the layout site plans provided was found to be less than optimal. The addition of trees to the external landscape, for example, would be helpful by providing shade and reducing the ambient temperature, thus having a proven impact on the levels of cooling energy required within buildings (Akbari et al., 1997, Simpson and McPherson, 1998).

#### *5.4.5.2 Building envelope design weaknesses (fabric)*

The use of efficient building fabric is essential for the construction of sustainable buildings in hot climates in terms of energy saving (Bojic et al., 2002, Li and Chow, 2005, Lukić, 2005, Lukić, 2003). The choice of material and shape for the envelope is usually taken into account during the design stage. The building fabric includes external walls, roof, floor and external windows, meaning that the resistance of these is crucial in maintaining the internal temperature for the longest possible time. For example, an external roof insulated by means of reinforced concrete slab can reduce the external roof temperature by an expected 10º to 15º C, due to the minimisation of sun heat (radiation gains) (Halwatura and Jayasinghe, 2007). The R-Value (resistance) of the building fabric is also instrumental in improving energy saving through the prevention or reduction of heat transfer, with efficient building fabric (in external walls) improving performance by 33% to 60% (Balaras et al., 2007). However, the sample dwellings in this study have used inadequate building fabric in their construction.

In these simulated dwellings, it was noted that the R-value in all cases is too low, which affects the resistance of the house envelope. For example, house (C) has an external wall of (mortar-normal brick-mortar/R-Value= 0.26 $m^2k/W$). This building fabric, combined with a poor design of external walls, results in increased energy needs for cooling the property in summer and heating it in winter to ensure continuous human thermal comfort.

The thermal characteristics of the external windows also play an important role in the reduction of heat and $CO_2$ emissions (Tian and de Wilde, 2011). According to Bokel (2007) "*The window position and the window shape influence the illuminances in a room. In this way the window position and the window size determine the electric lighting demand*" (Bokel, 2007). Single glazing was used in all analysed cases, resulting in increased energy demand due to inefficient prevention of heat transmission. Many solutions related to external glazing are available for retrofitting in these or similar properties. For example, triple glazing could be used, limiting the transmission of direct-beam solar irradiation and heat from the ambient environment, while still maintaining adequate levels of daylight inside the building (Askar et al., 2001, Tahmasebi et al., 2011).

#### *5.4.5.3 On-site renewable energy and behaviour of occupants*

According to Kanters, Wall et al (2014) "*Planning energy-efficient buildings which produce on-site renewable energy in an urban context is a challenge for all involved actors in the planning process"* (Kanters et al., 2014). On-site renewable energy plays a key role in the reduction of both energy consumption and $CO_2$ emissions by replacing fossil fuel combustion with clean, natural energy resources, such as solar radiation (Castillo-Cagigal et al., 2011, Eroglu et al., 2011). The southern region of Saudi Arabia has abundant solar radiation, generating approximately 2130 kWh/m² every year (Rehman et al., 2007). Since up to 15% of this solar radiation can be employed to generate electricity, meaning that up to 319 kWh/m²/ year could be generated for each property through the use of PV techniques. The greater the efficiency of the Photovoltaic (PV) cell with larger surface area exposed and the best position of the PV with respect to the sun will lead to a higher total of energy generation in the form of electricity (Medio, 2013). Increased knowledge of the implementation and use of PV systems in local contexts is required to enable large numbers of people in areas of high solar radiation availability, particularly in developing countries, to take advantage of this renewable energy source (Ulsrud et al., 2011). Unfortunately, on-site energy generation techniques were absent in all the analysed dwellings, despite the suitability of each site for PV use. The adoption of solar radiation panels would therefore be likely to have an immediate and noticeable impact on the levels of energy used and the $CO_2$ emission rate.

Occupants' behaviour has a major influence on energy consumption in the homes (Virote and Neves-Silva, 2012, Hendrickson and Wittman, 2010, Romero et al., 2013). Lifestyle, occupants activities and living standards are mostly responsible for the energy consumption in a house (Korjenic and Bednar, 2011). The wasteful behaviour of occupants within each dwelling examined here was also shown to play a major role in the high energy consumption figures recorded. For example, the annual energy consumption of house (B) is quite different from that of house (A) or (C), despite similarities in terms of local conditions and household members. This was because the occupants of house (B) travel abroad much of the time, and so have additional rooms that are unused for some months. Another example can be seen in the difference in annual energy consumption, according to the official bills, between flat (A) on one hand and flats (B) and (C) on the other, although all of the flats are of the same size, but with different numbers of occupants. The behaviour of occupants was generally shown to significantly affect the energy consumption patterns seen in both the official electricity bills and the final simulated result. Given this finding, it is suggested that public awareness campaigns be mounted to improve energy conservation behaviour.

### 5.4.6 Potential Energy Retrofitting Solutions

Based on the weaknesses discussed, the occupants could retrofit their dwellings to achieve energy savings. However, some solutions are unavailable for existing buildings because they would need to be integrated at the design stage. For example, it would not be possible to destroy the existing house envelope in order to construct an efficient one.

In this section, some possible solutions will be suggested. These will be retrofitted for the sample dwellings and then re-simulated using IES-VE. The new simulation results will be based on three suggested solutions: replace windows with efficient triple glazing; install shading devices; and install on-site energy generation through PV. The new simulation results (after retrofitting) will then be compared with the previous simulation results (before retrofitting) in order to evaluate the effectiveness of the proposed solutions. Each solution will be discussed individually.

#### *5.4.6.1 Replace the current glazing with efficient triple glazing*
Any existing building can install efficient double or triple glazed windows, which can slow heat transmission and mitigate direct heat from the sun. In these dwellings, the currently used glaze will be changed to efficient triple clear glazing, which is highly resistant (R-Value = 0.6 $m^2k$ /W) and uses argon gas between the panels of glazing.

#### *5.4.6.2 Install shading devices*
In these dwellings, some shading devices will be installed to increase shade around the building, thereby cooling the local environment. Different high-shade devices will be installed. Firstly, as the majority of Saudi houses already include a surrounding wall for privacy, a shade device will be installed on top of the surrounding walls (except the main elevation) to a height of 7 meters, except on the main elevation of the building, so that the nice view of the building will be preserved for the public. This measure will create shade around the building, reducing the temperature from direct sunlight during the hot seasons. Another shading device will be installed horizontally on top of the elevation of each window to block light and heat from the sun. This will support the installed triple glazing in slowing the transmission of external heat to the flat. An insulated external shutter (resistant 2.5 $m^2$.k/W) will also be installed in all dwellings, to perform similar functions.

#### *5.4.6.3 Install on-site renewable energy PV*
Each house will allocate no more than 10% of its roof area to site-renewable energy panels. This means that approximately 50 $m^2$ of roof area will be allocated for PV in house (A), 50 $m^2$ of roof area in house (B), and 50 $m^2$ of roof area in house (C). As the flats share the same building, with a total roof area of 481.5 $m^2$, 15 $m^2$ of the roof area will be allocated for the PV system for each flat.

### 5.4.7 Validation Of The Retrofitting Solutions: Simulation Results Of The Modified Models
Each dwelling in this study was retrofitted with the limited solutions described above. The results of the simulation are displayed in Figure 5.51. This figure presents a comparison of the new results (after retrofitting) with the previous results (before retrofitting), indicating that energy savings may increase from 20% to as much as 34%. In the case of house (B), it is clear that the solar radiation accounted for over 50% of energy because the energy demand in this dwelling is lower than in the others.

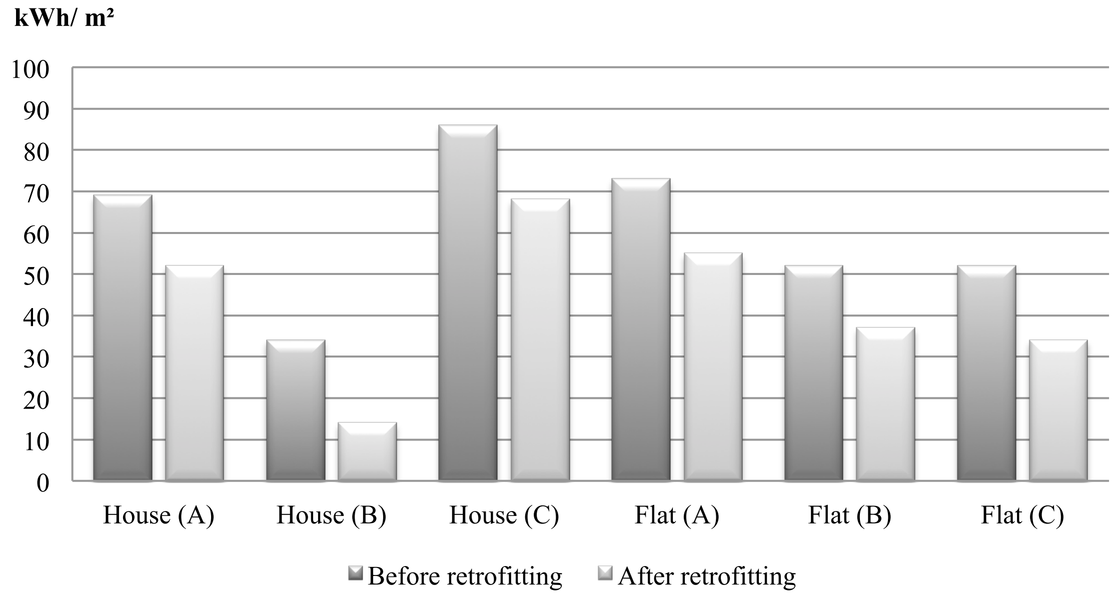



**Figure 5.51 Comparison of Annual Energy Consumption (kWh/m²) In The Current Situation And After Simulated Modifications**

Through an increase in the area of PV, energy generation from solar radiation will also increase. These results suggest that a potentially dramatic reduction of energy consumption could be achieved for those dwellings which are still at the design stage, and which would therefore have access to many other solutions related to the choice of fabric and shape.

## 5.5 Summary

The case study described here investigated energy consumption in typical domestic houses and flats by examining the energy consumption and $CO_2$ emissions associated with different properties in Saudi Arabia. High electrical energy consumption was observed in these typical houses and flats (e.g up to 185 kWh/ m² in Jeddah or 203 kWh/m² in Riyadh)

Many design weaknesses were identified at this stage in relation to architectural design, mass, landscaping and house envelope design. In more detail; the typical housing area was large compared with those developed countries in EU. This leads to extra use of energy, resulting in higher $CO_2$ emission rates. House envelope design is poor with R-

Value 0.26 m²k/W. This resistance is very low compared with the passive house code in Germany. The building shape found in existing homes allowed solar heat in, resulting in higher energy demand for cooling systems, whereas in developed countries, roof slope, shape, and attics create insulation between the external environment and internal atmosphere. The weaknesses identified by the researcher included architectural and construction designs; in view of these some target solutions were proposed. However, more serious steps must be taken in order to minimise the energy consumption by existing houses, as well by new houses in the future. The current average electricity consumption is too high when compared with the codes established and abided by in developed countries (Institute, 2008), and this problem needs to be addressed and resolved.

Implementing the suggested solutions in existing dwellings in Saudi Arabia will certainly require complementary measures. According to the Ministry of Electricity, utility bills sent to customers already subsidised. This policy can be translated into other measures such as (a) ensuring that property owners energy retrofit their homes: the government can help property owners financially with the energy retrofitting of their homes rather than subsidising electricity bills; (b) increase public awareness by encouraging people to energy retrofit their dwellings by emphasizing potential reduction in electricity prices while maintaining comfort conditions; and (c) establishing an energy governance approach reflected in stringent policies and regulations that would assist in implementing and monitoring energy savings and $CO_2$ emission reduction across the country.

Some limited retrofitting solutions have been suggested and applied in these houses and flats with the goal of reducing the annual energy consumption for each property. These solutions were separately retrofitted in each house and flat model and then simulated again by IES-VE software. The new results suggest that a reduction of energy consumption based on the suggested solutions may potentially range from 15 to 37%. Therefore, this research can provide general recommendations for existing and new dwellings.

Based on the different properties analysed, as well as the final results regarding the energy consumption at Saudi houses and flats, the weakness identified in terms of construction materials and architectural style, and the various behaviour patterns in different households, the following chapter will seek a sharp reduction in energy consumption in new residential buildings in hot climates. Possible solutions to this challenge include the creation of new techniques for the construction of suitable building fabric, devising viable forms of onsite renewable energy and integrated architectural solutions, including shading devices and landscaping.

# Chapter 6 : Consensus-Based Low Carbon Domestic Design Framework For Sustainable Homes

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## 6.1 Introduction

This Chapter proposes a low carbon domestic design framework for sustainable homes in Saudi Arabia; a country characterized by a rigorous climate and unique regional socio-cultural features. The proposed framework is informed by (a) the preceding in-depth investigation of the Saudi domestic building stock, including landscaping, massing, space layout, building fabric, on-site renewable potential, and occupants' lifestyles; and (b) a consultation with 40 experts across Saudi Arabia. The consultation was carried out using the Delphi Technique in three rounds as it was described in the methodology chapter 3 section 3.3.3 pp. 76-84. The proposed framework incorporates factors concerning architectural design strategies, building envelope design, and on-site renewable energy strategies for Saudi Arabia, taking into account socio-cultural considerations. A consensus between the consulted experts was achieved. The proposed framework is applicable and suitable for Saudi Arabia and the broader Middle Eastern region. This stage also refers to the design weaknesses and proposed sustainability strategies for the Saudi residential sector that were identified in Chapters 4 and 5 of this thesis. The chapter is structured into three main categories; (a) results and analysis, (b) established low carbon domestic design framework for sustainable homes, and (c) summary.

## 6.2 Result And Analysis

The questionnaire was distributed to many experts in Saudi Arabia, but in the end forty of them agreed to take part in all three consultation rounds. As planned, each expert was required to be involved in all three rounds in order to develop the model framework for a design strategy. One of the challenges faced by this study was how to ensure that the same experts were involved in all three consultation rounds. Although some experts withdrew after the first or the second round, 40 experts saw the value of the study and continued in all three rounds, cooperating with the researcher by providing new ideas, responding to questions and keeping in touch with the researcher. The chart below (Figure 6.1) shows the experts appointed in this study.


**Figure 6.1 Experts Appointed For Delphi Panels Consultation**

The following section will present the analysis of the findings from the three rounds of consultations with the experts. As the consultations involved many different criteria of design strategies for designing low energy homes in Saudi Arabia, the analysis will be presented under three main categories: (a) analysis of architectural design techniques and strategies, (b) analysis of building envelope design techniques and strategies, and (c) analysis of on-site renewable energy strategies and cultural issues.

### 6.2.1 Analysis Of Architectural Design Strategies

Under this category, there are multiple design techniques and strategies related to the architectural design and form of the building. These design techniques and strategies were assessed and approved by the experts through three different rounds, and relate to: landscaping, massing and space layout, windows design, shading device design and strategies, cooling and heating system (HVAC), and natural ventilation.

- Landscaping, massing and space layout

The form of a building involves various considerations, including the architect's design principles and the client's requirements. It is extremely important to take into account during the designing stage, the environmental requirements. For example, Saudi Arabia has a hot and challenging climate, requiring specific architectural interventions in order to keep the energy consumption to a minimum. During the consultation with experts regarding the form of the buildings for hot environments, it was found that some architectural features were more efficient in hot climates like that of Saudi Arabia. These features include shading device design strategies, the efficient indoor design of the building, orientation of the building, optimal design of the building shape, size of the building and external landscaping. Figure 6.2 shows the average rating that experts gave to landscaping, massing, and space layout. It can be seen that external landscaping, designed to cool the external environment of the building and provide shade during hot periods of the day, is considered to play the most significant role in reduce the need for air conditioning and thus saving energy. Some of the other general architectural design features, such as shading device strategies and building shape, will be analysed individually in more depth.

| Landscaping, Massing and Space Layout | Mean | IQR |
|---|---|---|
| (1) Orientation of the building south facing | 3.33 | 1 |
| (2) Shading devices | 4.15 | 1 |
| (3) Minimizing building size as possible | 3.25 | 1 |
| (4) Optimal design of building shape | 4.28 | 1 |
| (5) Internal subdivisions of the building | 3.48 | 1 |
| (6) Increase green areas around the building | 4.38 | 1 |
| (7) Use green building techniques | 4.15 | 1 |
| (8) Slope shape to minimise exposure to sun's heat | 3.27 | 1 |
| (9) Use semi-detached or terraced house configuration | 3.25 | 1 |
| (10) Use light colours for external walls | 4.25 | 1 |
| (11) Design the building to take wind direction into account | 4.47 | 1 |
| (12) Consider fitting the building within its surrounding context | 4.4 | 1 |
| (13) Reduce the width of the south facing "façade" as much as possible | 3.35 | 1 |

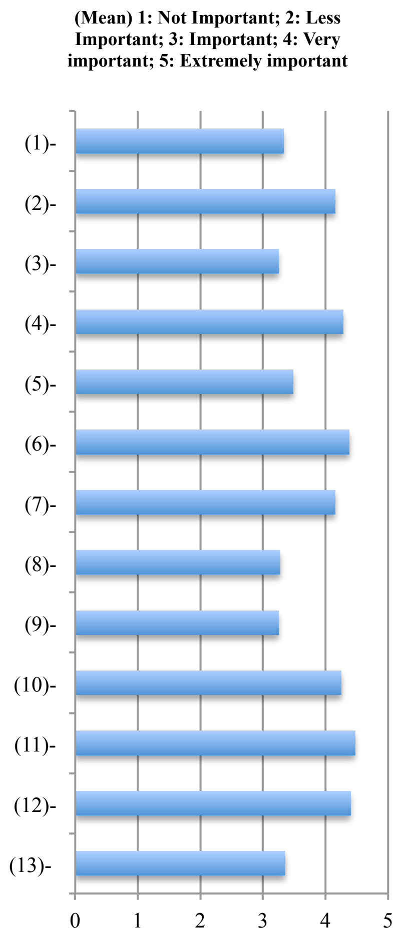



**Figure 6.2 Landscaping, Massing, And Space Layout: Average Rating Given By Experts**

All of these design techniques and strategies were given a rating of more than 3 out of 5, which meant that they were considered either important, very important, or extremely important.

- Window Design

Another architectural design feature that must be considered for reducing energy consumption is the optimal design of external windows. The most important consideration is how to design the external windows so they provide natural light and reduce the gain of solar heat as much as possible. Window design techniques and strategies for saving energy were investigated by the experts in the three consultation rounds (see Figure 6.3).

| Windows' design | Mean | IQR |
|---|---|---|
| (1) Reduce windows area | 3.8 | 1 |
| (2) Reduce the number of windows | 3.6 | 1 |
| (3) Use canopies on top of windows to prevent from sun heat | 4.17 | 1 |
| (4) Use colour glaze for external windows | 3.48 | 1 |
| (5) Place the windows in the north side, with solar collection in the south face | 3.95 | 0.25 |
| (6) Reduce the size and number of southern windows | 3.63 | 1 |
| (7) Reduce the number of windows on the east and west sides | 3.2 | 1 |
| (8) Grow grass in front of each window | 3.08 | 0.25 |

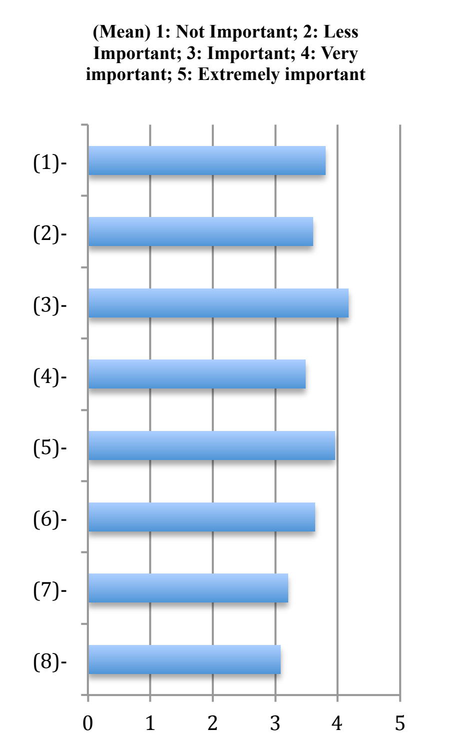



**Figure 6.3 Window Design Techniques And Strategies: Average Rating Given By Experts**

It can be seen that many techniques can be applied and implemented in future buildings in hot climates, e.g. use canopies on the top of windows as shade to prevent the solar heat. Moreover, it can be seen in Figure 6.3 that reducing the number and sizes of windows is one of the most important strategies for saving energy as hot air passes through external windows to the indoor atmosphere, resulting in extra energy being consumed to cool the building inside.

- Shading Device Design and Strategies

For hot climate countries, shading devices are important to cool the surrounding area of the building and reduce the air conditioning load used to cool the inside the building. Figure 6.4 shows the rating given by the experts on the most effective shading device strategies for buildings in Saudi Arabia.

| Shading Device | Mean | IQR |
|---|---|---|
| (1) Use high shading devices around the building on top of external walls | 3.15 | 1 |
| (2) Use internal and/or external shutter for windows to prevent unwanted solar gains | 3.88 | 0 |
| (3) Use efficient court yard landscaping design to provide shade around the building | 4.1 | 0.25 |
| (4) Use horizontal canopy to create shade | 3.73 | 1 |
| (5) Use sun louver techniques | 3.98 | 0 |
| (6) Shading in Ventilated Facades | 4.15 | 0 |
| (7) Use planting shades instead of steel shades in windows | 4.05 | 0 |
| (8) Use sun reflection design techniques | 3.7 | 0 |
| (9) Employ Building Management Systems (BMS) to control the lighting for the whole building | 4.05 | 0 |
| (10) Use roof shading techniques | 4.03 | 0 |

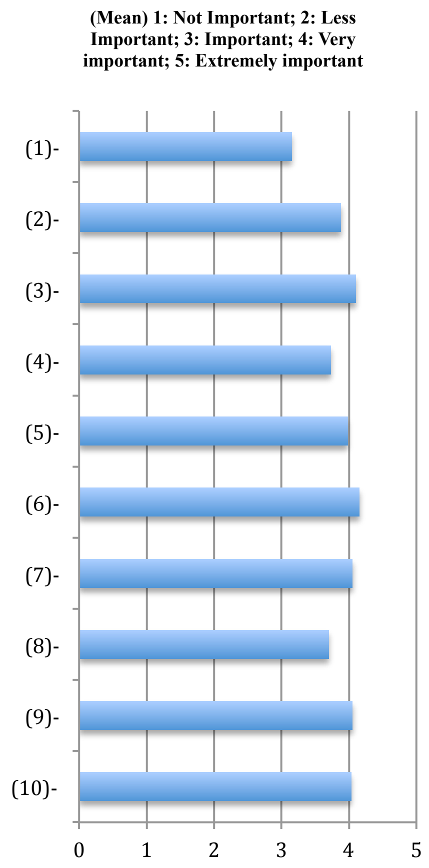



**Figure 6.4 Shading Device Design Techniques And Strategies: Average Rating Given By Experts**

It can be seen that there are many design techniques and strategies related to shading device and many of these were considered equally important (the average rating being 4). This underlines the importance of optimising the design of shading devices for buildings in hot climate countries such as Saudi Arabia. In a hot climate like that in Saudi Arabia, the top floor rooms of buildings will require extra energy to cool the internal environment. Therefore, roof shading techniques or providing shade for the roof is considered one of the most important techniques to use in order to reduce energy consumption and the need for air conditioning units.

- Cooling and Heating System (HVAC)

Due to the hot climate in Saudi Arabia, there is a demand for air conditioning throughout the year in order to create a comfortable indoor environment. There are some design strategies to control the use of air conditioning or cooling systems in order to achieve energy conservation where possible. Figure 6.5 provides alternative strategies that can be used to conserve energy in domestic buildings in Saudi Arabia.

| HVAC | Mean | IQR |
|---|---|---|
| (1) Divide the internal rooms in the building into zones to create separate cooling and/ or heating units and use rooms when the need arises only | 4.25 | 1 |
| (2) Use sensors for air conditioning that control temperature of the rooms | 4.35 | 1 |
| (3) Use mechanical ventilation techniques | 3.73 | 1 |
| (4) Use ground heat exchange techniques | 3.52 | 1 |

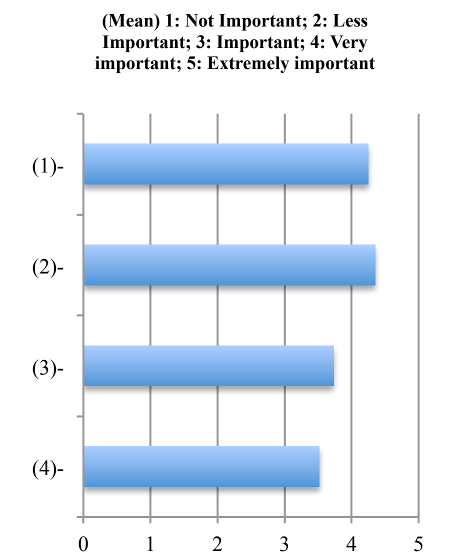



**Figure 6.5 HVAC Design Techniques And Strategies: Average Rating Given By Experts**

Air conditioning units and mechanical ventilation require energy but this can be controlled by dividing the building into zones and having separate cooling or heating units to save energy. Also, according to the experts, using sensors that control the temperature of the room is very important but they are not implemented by people in the home. The cheap price of energy (Alyousef and Stevens, 2011) and a lack of public awareness about levels of energy consumption may help to explain why such measures are not being taken in an attempt to make domestic living more energy efficient. These techniques should be used in future homes to design efficient cooling systems with the lowest energy consumption.

- Natural Ventilation

Natural ventilation can be an optional solution in some areas of Saudi Arabia, such as the southern region, which is cooler than other areas of the country. Natural ventilation will support the HVAC system and in extremely hot areas, natural ventilation can be an option in cold seasons. Figure 6.6 shows that experts consider the orientation of the building and placing the windows in the wall in order to have air stock, to be the most important strategies (both given a rating of more than 4 out of 5). The indoor design of the building is dependent on the client's social requirements but it can be designed with natural ventilation in mind by using an open plan design in order to promote airflow.

| Natural Ventilation | Mean | IQR |
|---|---|---|
| (1) Use windows to ventilate the building | 3.02 | 0.5 |
| (2) Use ventilation tower technique to create air shafts/stacks | 3.52 | 1 |
| (3) Design the indoor of the building by open plan in order to provide interior airflow | 3.75 | 1 |
| (4) Each room should be designed to have two opening windows to promote airflow | 3.27 | 1 |
| (5) Place windows in the wall in order to have natural light and air stock | 4.28 | 1 |
| (6) Design the building so as to have space inside which will support the natural ventilation | 4.03 | 0 |
| (7) Orientate the building to the north to provide ventilation and avoid solar heat | 4.22 | 1 |

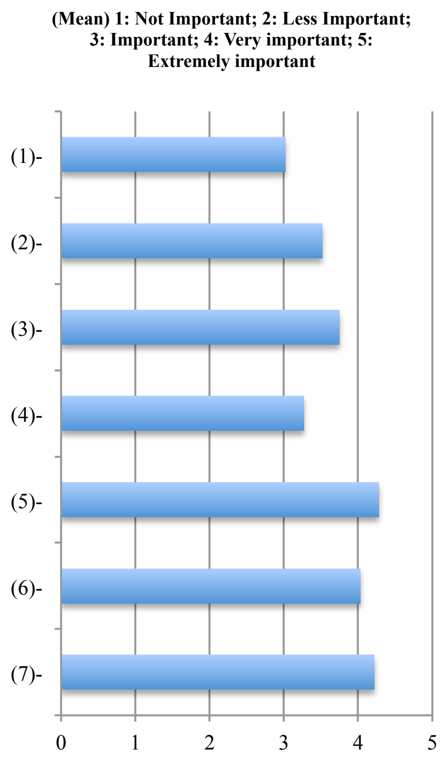



**Figure 6.6 Natural Ventilation Design Techniques And Strategies: Average Rating Given By Experts**

Having two opening windows for each room is one of the strategies advised and approved by the experts in order to provide airflow in the windows in the cool seasons. In addition, the ventilation tower is another possible ventilation system. These design strategies, for a natural and efficient ventilation system that meets the occupant's needs, would support the architect when designing future domestic buildings.

### 6.2.2 Analysis Of Building Envelope Design Strategies

Selecting the materials in designing the building envelope is an extremely important consideration within the design stage. Building envelope design strategies for hot climates have been investigated by the experts in this study. The building envelope involves external walls, the roof, the floor and the external glazing. Figure 6.7 shows some design strategies to be considered by consultants within the design stages.

| Building Envelope | Mean | IQR |
|---|---|---|
| (1) Thicknesses of house envelop | 4.28 | 1 |
| (2) Conductivity of materials | 4.47 | 1 |
| (3) Resistance of the materials | 4.42 | 1 |
| (4) Type of insulation materials | 4.72 | 0 |
| (5) Use modern construction materials which have high insulation and are available in the country | 4.42 | 1 |
| (6) Use efficient finishing materials with high R-Value | 4.7 | 0.5 |
| (7) Use a suitable construction material in terms of coolness retention | 4.47 | 1 |

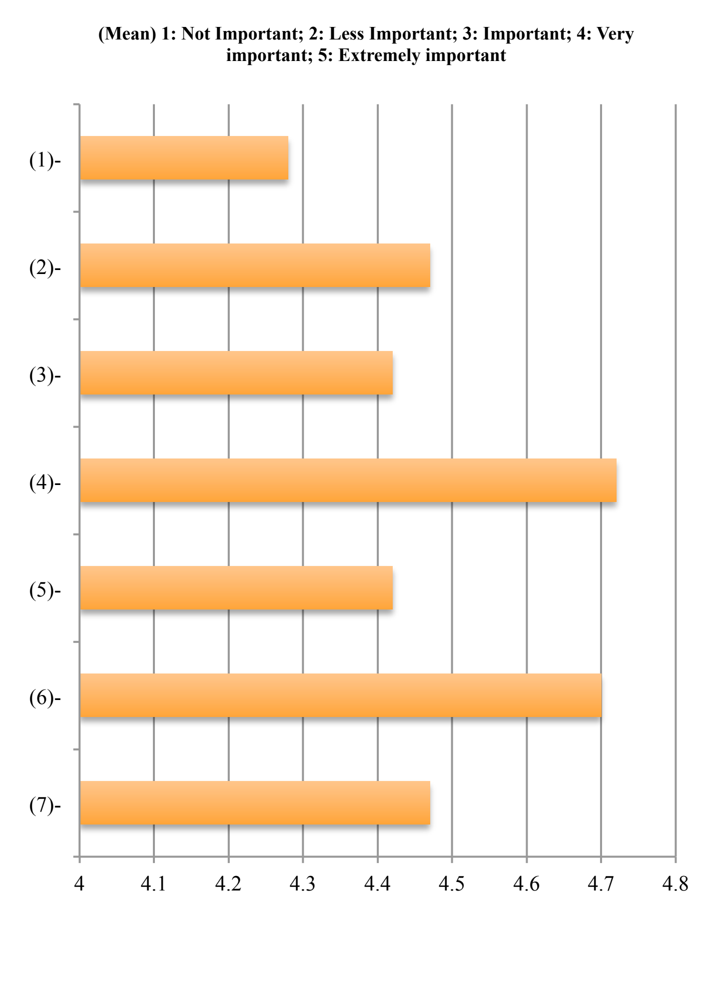



**Figure 6.7 Building Fabric Design Techniques And Strategies: Average Rating Given By Experts**

It can be seen that, all experts agreed that it is very important to design an efficient building envelope to prevent or slow down the passage of external hot air from the external to the internal atmosphere. For example, selecting a finishing material seems to be extremely important in order to give the building smart elevation and to provide resistance for thermal transmission. Using construction materials with low conductivity is also very important as the thickness can reduce the U-value of the external envelope of the building. The selected construction materials depend on their availability in the country. According to the experts, efficient insulation is very important.

- External Walls Design

Efficient design of external walls is important in hot climates and involves consideration of the insulating attributes of used construction materials and the techniques of designing the external walls. Figure 6.8 presents the design techniques and strategies related to designing external walls efficiently in order to save energy where possible.

| External Walls | Mean | IQR |
|---|---|---|
| (1) Design external walls with Mud in order to be highly insulated | 3.13 | 1 |
| (2) Design external walls with solid red- clay brick | 3.58 | 1 |
| (3) Use Stone built external walls | 3.08 | 0 |
| (4) Use cavity techniques in external walls | 4 | 0 |
| (5) Use volcanic bricks as an efficient construction material | 3.88 | 0 |
| (6) Use double skin walls in designing the external walls | 3.9 | 0 |

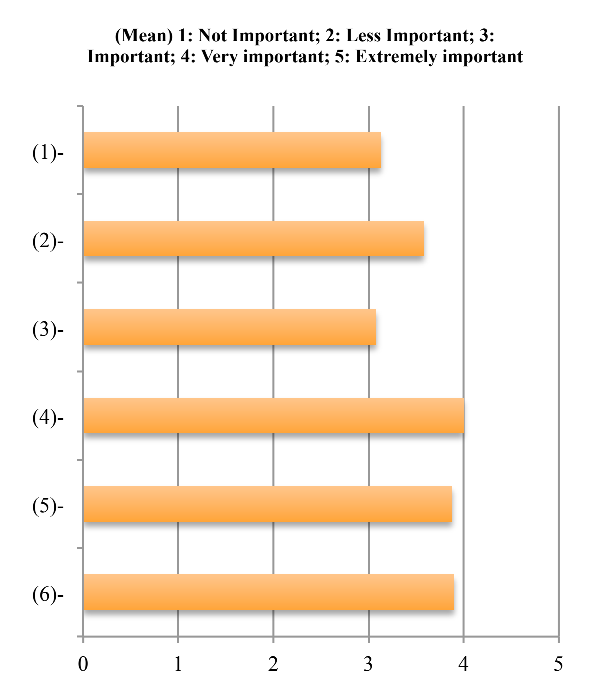



**Figure 6.8 External Wall Design Techniques And Strategies: Average Rating Given By Experts**

It is clear that there are multiple strategies and techniques to design the external walls in Saudi Arabia. Using cavity in the design of external walls seems to be the most important consideration according to the experts in this study, while using the double skin wall technique is also considered an important feature in the design of future homes in Saudi Arabia.

- External Glazing

Many design strategies and techniques, used to save energy in buildings, are related to the design of the external glaze, some of which aim to reduce solar heat and consequently reduce energy consumption. Six design techniques and strategies have been identified as being suitable and effective for use in Saudi Arabia (see Figure 6.9).

| External Glazing | Mean | IQR |
|---|---|---|
| (1) Increase the thickness of glazing | 3.6 | 1 |
| (2) Use double or triple glazing with air between glazing panels | 4.17 | 1 |
| (3) Use double or triple glaze with argon gas between glazing panels | 4.08 | 0 |
| (4) Use highly air tight windows | 4.45 | 1 |
| (5) Use foam glazing in external windows | 3.55 | 1 |
| (6) Use plaster for glaze insulation for external windows | 3.5 | 1 |

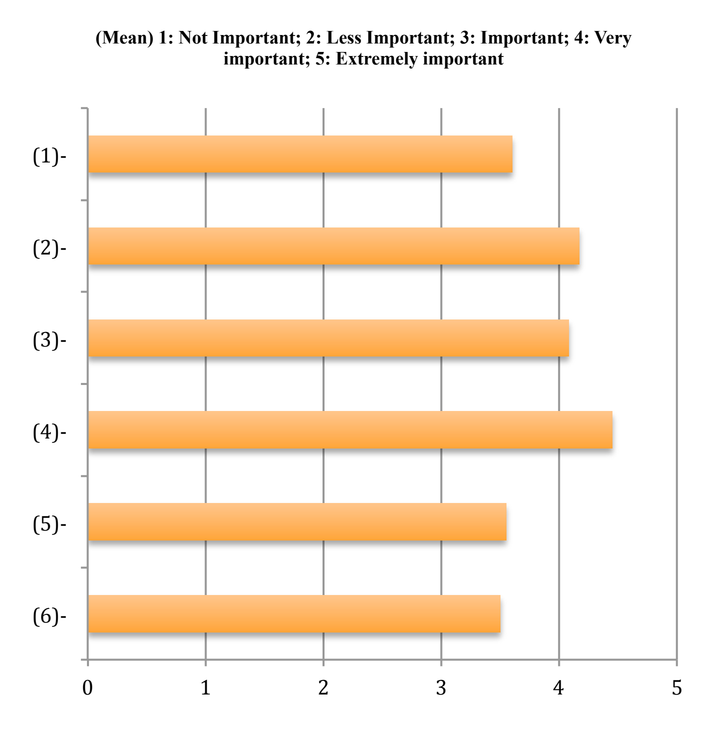



**Figure 6.9 External Glazing Design Techniques And Strategies: Average Rating Given By Experts**

In summary the experts' perspective shows that whilst all of the above techniques are important (average rating 3 out of 5) some are considered very important (average rating 4 out of 5). For example, the use of highly air tight windows is considered the most important feature of external glazing design. Using multiple glazed units (either double or triple) with air or argon gas between the panels is also seen as a crucial feature in maximising efficiency for buildings in the Saudi Arabian environment. Additional types of glaze can be used such as foam glazing. The thickness of each single glaze in the window is important as increasing the thicknesses will increase the efficiency of the glaze.

- External Roof and Floor Design

In hot climates such as those in the Middle Eastern region, the roof and floor design will have an impact on energy consumption in the building. Figure 6.10 shows the experts' ratings of possible design strategies and techniques for achieving an efficient, energy-saving external roof and floor.

| External Roof and Floor | Mean | IQR |
|---|---|---|
| (1) Design the external roof above the structure concrete with rain insulation and wood materials | 3.2 | 1 |
| (2) Design the external roofs above the structure concrete by efficient insulation materials and concrete tiles | 4.33 | 1 |
| (3) Design the external roofs above the concrete structure by green grass to increase the insulation | 3.85 | 1 |
| (4) Create a cavity above the structure, ventilated at night to prevent direct sun heat | 3.88 | 1 |
| (5) Use mud insulation, mortar and concrete tiles in floor | 3.2 | 1 |
| (6) Use wood insulation materials | 3.05 | 0.25 |
| (7) Use a thick layer of sand and concrete tiles In floor | 3.3 | 1 |
| (8) Use a layer of concrete including sand and concrete tiles in floor | 3.2 | 1 |
| (9) Use natural stone in floors | 3.7 | 1 |

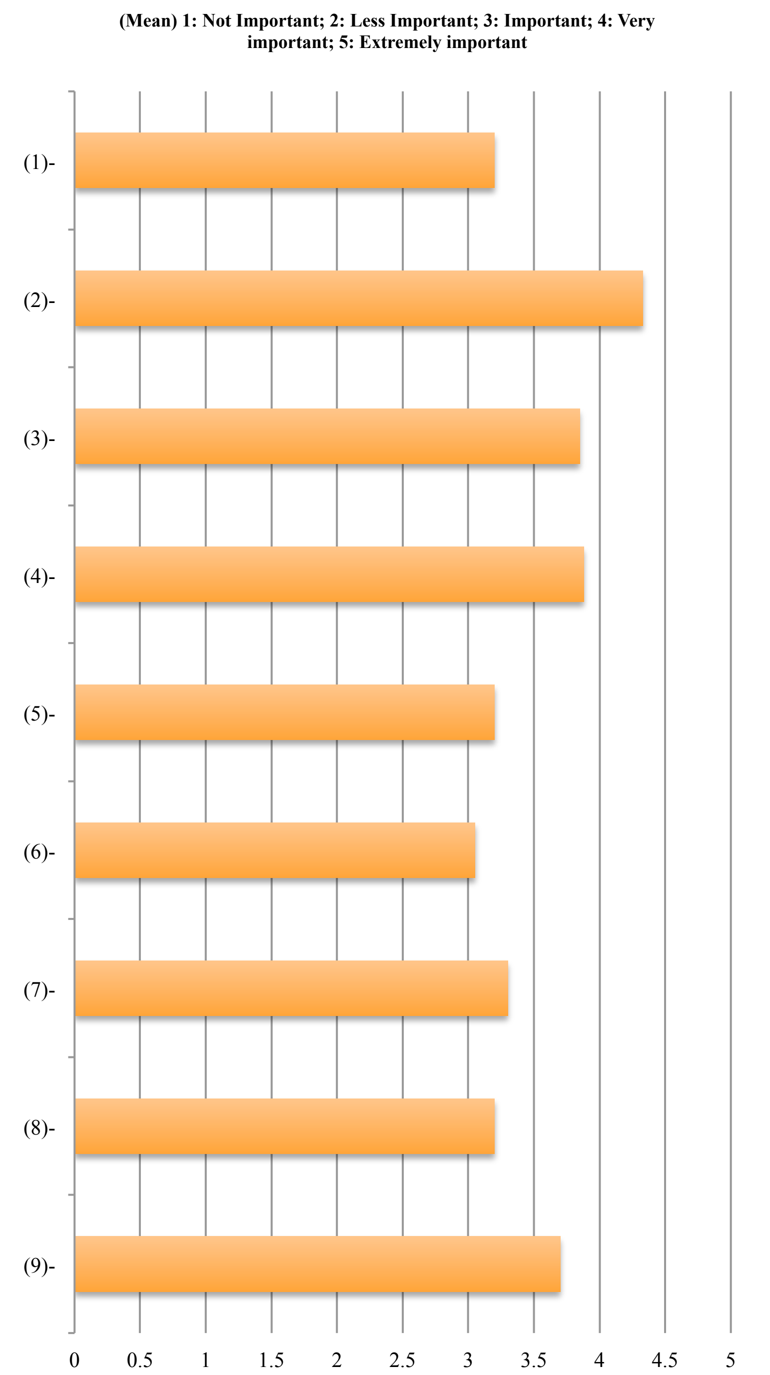



**Figure 6.10 External Roof And Floor Design Techniques And Strategies: Average Rating Given By Experts**

It can be seen that, many techniques and design strategies were approved in the consultation with experts in order to design this type of house envelope in a Saudi Arabian environment. Using efficient insulation materials above the concrete roof structure in the external roof is rated as the most important consideration according to experts, closely followed by creating a cavity above the structure which is ventilated at night to prevent the sun's direct heat. For floor insulation, using natural stone scores highly as an efficient way of reducing energy consumption and is a resource which is available in Saudi Arabia. Using a thick layer of sand with concrete tiles is also another popular option.

### 6.2.3 Analysis Of On-Site Renewable Energy Strategies And Cultural Issues

Saudi Arabia is ideally placed to make good use of natural resources such as solar radiation (Hepbasli and Alsuhaibani, 2011) that should be used efficiently in residential buildings. The experts in this study have investigated many design techniques and strategies related to possible renewable energy sources in Saudi Arabia. It was found that there are many techniques and design strategies which are suitable for the Saudi Arabian environment and market. Figure 6.11 shows the techniques and design strategies that experts believe should be implemented in the Saudi Arabian construction industry (in a residential environment).

| On-site Renewable Energy | Mean | IQR |
|---|---|---|
| (1) Use PV on top of the south face of the building | 3.6 | 1 |
| (2) Use PV on top of the east and west faces of the building | 3.3 | 1 |
| (3) Use wind energy generation | 3.4 | 1 |
| (4) Use new and efficient PV available on the market | 3.77 | 1 |
| (5) Heat the DHW by solar radiation | 4.35 | 1 |

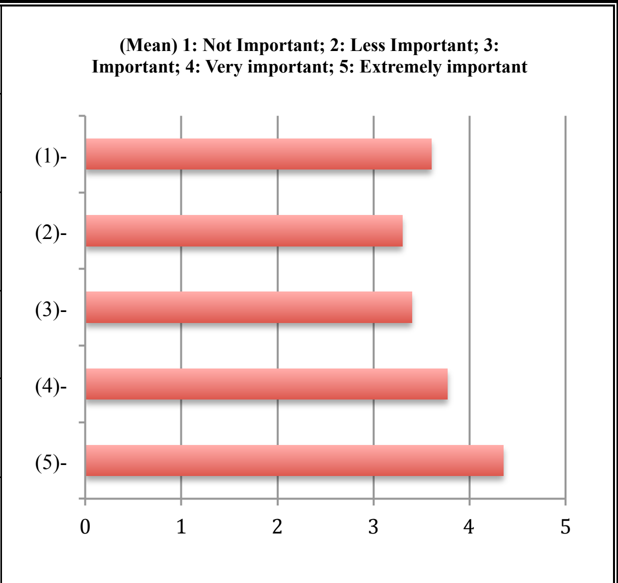



**Figure 6.11 On-Site Renewable Energy Design Techniques And Strategies: Average Rating Given By Experts**

Solar radiation is the main available source and many techniques can exploit this solar energy to generate electricity. One of these strategies is using the PV panels on top of the building so that they are south-facing. However, this is dependent on the location of the building. For the sites and buildings that are not south facing, the other option is to orientate the PV to the east and/or west to have the benefit of solar energy in order to generate electricity. Installing the recent efficient type of PV panels is also important. Heating up the domestic water by solar radiation is the most popular option and is suitable for buildings in Saudi Arabia where the water tank for domestic use is on the top of the building. Using PV to heat up the domestic water is more efficient and one of the techniques that can be implemented to reduce using boilers as much as possible.

Cultural image in Saudi Arabia has an impact on the building design so the experts looked at how to change some of the energy-saving design strategies to suit the culture of Saudi Arabia. Figure 6.12 shows the experts' ratings of energy-saving design strategies that take into consideration the importance of cultural image in Saudi Arabia.

| **Cultural Image** | **Mean** | **IQR** |
|---|---|---|
| (1) Reduce unnecessary spaces which add no value to the building | 4.3 | 1 |
| (2) Reduce area of rooms that have highest use period e.g. bed rooms | 3.25 | 1 |
| (3) Use the second floor of the building for rooms that have less usage period (e.g. guest rooms) and use the ground floor for rooms that have high usage period e.g. bedroom or sitting area | 3.73 | 1 |
| (4) As the underground is cooler, use the underground level instead of the over ground levels | 3.15 | 1 |

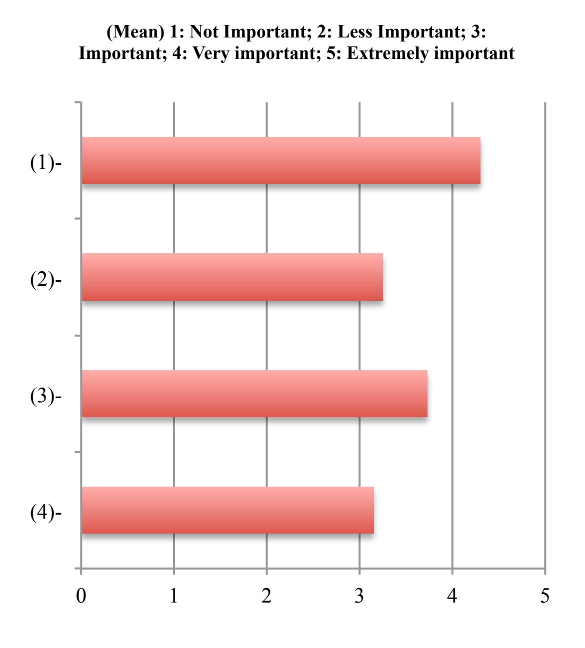



**Figure 6.12 Social And Cultural Aspects Of Techniques And Strategies: Average Rating Given By Experts**

It is clear that, reducing unnecessary spaces which add no value to the building should be the top priority according to the experts. The unnecessary space could be the huge space of guest rooms which are separate (one for men and another for women) and are used only once or twice a month. To make energy consumption in homes more efficient, it is also recommended that the area of rooms with the highest energy consumption, such as bedrooms, are reduced in size. These rooms are fairly spacious in existing homes as found by the researcher in chapter 5 (Aldossary et al., 2014a, Aldossary et al., 2014b) but reducing these areas to fit with occupant's needs is an efficient strategy that should be implemented in future housing in Saudi Arabia.

In addition, changing the location of rooms can also reduce energy consumption. This can be achieved by locating the rooms which have the highest energy consumption levels (e.g. bed rooms or family sitting areas) on the ground floor while the rooms which have the lowest energy consumption levels (such as the kitchen and the guest rooms) on the first floor. The top floor will create insulation for the ground floor rooms, which have the highest energy use, thus reducing overall energy consumption levels in the home.

### 6.2.4 Tools Used To Assess The Level Of Importance Of The Design Strategies In The Framework

The established framework supports the architects and civil engineers when designing sustainable low energy homes in Saudi Arabia. The framework contains various criteria with different levels of importance. It is necessary to offer refer to the statistical level of importance concerning the criteria involved in the framework. Over three different Delphi rounds, the experts individually assessed and measured the importance of each criterion to the framework. The investigation was performed from the perspective of the applicability of the criteria to Saudi Arabia, and the level of importance of each criterion to enable the architect flexibility when using the framework. The level of importance measured by each individual criterion will support the architect and civil engineer, and the design strategies will be more efficient and according to occupants' needs, budgets and the site conditions. Hence, two main measurement tools have been employed to assess the framework: (a) the level of importance, and (b) the consensus of experts regarding the level of importance.

Firstly the 5-point Likert scale was used to assess the importance of each criterion where:

1 = Not important
2 = Less important
3 = Important
4 = Very important
5 = Extremely important

For each criterion, the rating average was measured as illustrated below (SurveyMonkey, 2015):

$$\frac{x_1w_1 + x_2w_2 + x_3w_3 \ldots x_nw_n}{\text{Total}}$$

w = weight of answer choice

x = number of responses to the answer choice

According to the above measurement tool, the level of importance for each individual criterion was assessed in the framework, and provided to support the architect and civil engineers to use suitable criteria in their projects. The mean point (level of importance 1 to 5) for each criterion in the framework has been displayed in Figures from 6.2 to 6.12. It is important to highlight that, all the strategies utilised in the framework are applicable to the Saudi Arabian context and assessed as important to extremely important.

### 6.2.5 Achieving Consensus Amongst Experts For The Design Strategies

The other tool employed in the framework concern measuring the consensus (agreement of applicability and important level) for each individual criterion, is interquartile range IQR. Delphi consultation is a systematic approach, that involves experts working to achieve a consensus (Adler and Ziglio, 1996). According to Paliwoda (1983) “The total group response or consensus will successively move toward the "correct" or "true" answer” (Paliwoda, 1983). Many statistical methods can be used to measure if consensus has been achieved; such as (i) interquartile range (IQR), (ii) mean and rank, and (iii) standard deviation method (Bailie, 2011). The IQR has been chosen as the mathematical method to measure consensus for each individual criteria in the framework, as it promotes stronger measurements compared with the other statistical methods (Murphy et al., 1997). The interquartile range is defined and presents the variance between the lower quartile and the upper quartile.

*IQR= Q3-Q1*

*Q3= upper quarter*

*Q1= Lower quarter*

Consequently, an IQR range of 20% on the rating scale is deemed an adequate basis on which to establish expert consensus (Rayens and Hahn, 2000). Therefore, the IQR ($0 \leq IQR \leq 1$) is used to measure consensus accuracy on a 5-point Likert scale (Rayens and Hahn, 2000) (1: Not important; 2: Less important; 3: Important; 4: Very important and 5: Extremely important). Each criterion have been assessed according to the equation above and approved as $0 \leq IQR \leq 1$. Figures from 6.2 to 6.12 illustrate the IQR for each individual criterion, while Table 6.1 summaries the IQR for the framework. Table 6.1 presents the status of consensus achieved for the design techniques and strategies identified through the consultation. These statistical analyses demonstrate that, this framework was agreed upon by the experts and was applicable to the Saudi Arabian climate, considering the availability of local raw materials and cultural requirements.

**Table 6.1 Status Of Consensus For The Design Techniques And Strategies**

| Framework Categories | | Number of Criteria | Status of Consensus |
|---|---|---|---|
| Architectural Design | Landscaping, massing and space layout | 13 | ✓ Achieved |
| | Window's Design | 8 | ✓ Achieved |
| | Shading Device | 10 | ✓ Achieved |
| | HVAC | 4 | ✓ Achieved |
| | Natural Ventilation | 7 | ✓ Achieved |
| House Envelope Design | Building Envelope | 7 | ✓ Achieved |
| | External Walls | 6 | ✓ Achieved |
| | External Roof | 4 | ✓ Achieved |
| | Floor Design | 5 | ✓ Achieved |
| | External Glazing | 6 | ✓ Achieved |
| **On-Site Renewable Energy** | | 5 | ✓ Achieved |
| **Cultural Aspects and Image** | | 4 | ✓ Achieved |

As presented in Table 6.1, all the design techniques, in each framework category, were agreed by the experts to be suitable for the Saudi Arabian climate, environment and culture and so a consensus was achieved. From this, a low carbon domestic design framework for sustainable homes can be established to support developers, architects, civil engineers and decision makers in the construction industry to design energy-efficient homes for Saudi Arabia in the future.

## 6.3 Established Framework Design for Low Carbon Homes

Following the investigation into the various design techniques and strategies that can support architects and civil engineers to design low energy homes in Saudi Arabia (to suit the culture and climate), the final low carbon domestic design framework for sustainable homes has been established, as shown in Figure 6.13.

Each housing design will be considered as a specific consideration. To design a sustainable low energy home in Saudi Arabia, it is significant to take into account the environmental conditions (hot climate), occupants needs, and budget, in order to offer a sustainable low energy home that meets clients' needs. Hence, the low carbon domestic design framework established offers various options in terms of design criteria. These design criteria relate to the building shape, mass, envelope and architectural concepts, and meet the local population's requirements, from general and environmental perspectives. Moreover, this framework provides various design criteria for the housing envelope designs, taking into account local raw materials in Saudi Arabia. The specific design consideration is flexible and employs the design framework. Building professionals, architects and civil engineers can use and adopt the framework and consider a specific design when creating housing for their clients. The design strategies in the framework were ranked in terms of importance in order to provide the designer with the requisite flexibility to use the best option for his client.

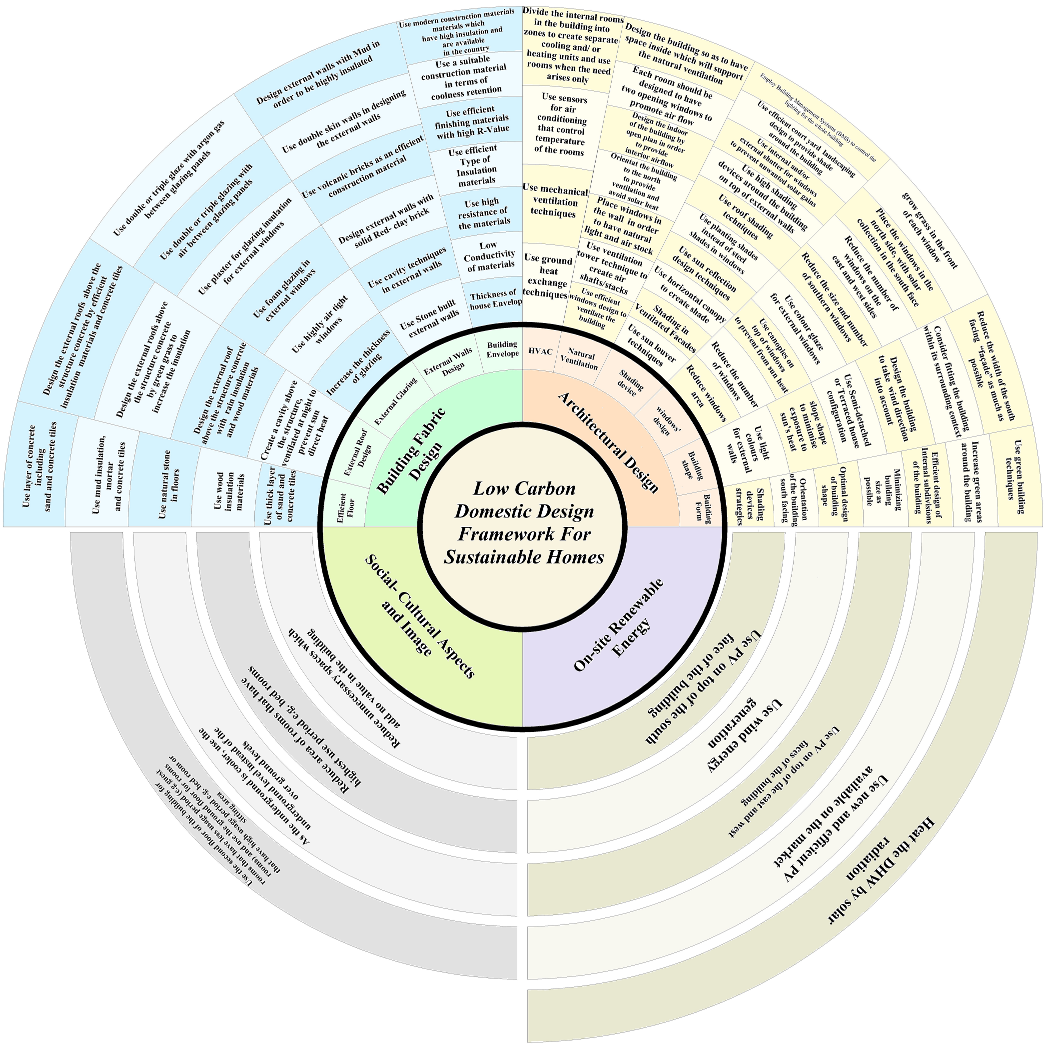



Figure 6.13 Low Carbon Domestic Design Framework For Sustainable Homes For The Saudi Arabian Climate And Culture

This figure contains four main categories with each category involving many design techniques and strategies in order to design sustainable homes in hot climates (Saudi Arabia). The discussion of the established model will present three main categories: architectural design strategies, building envelope design strategies and on-site renewable energy techniques and strategies\ socio-cultural issues.

Building professionals, such as architects, civil engineers, and other subjects related to the construction industry or the built environment have graduated from university and now have different comprehensive curriculums. These curriculums could cover different fields in the construction industry; such as, structure, design, infrastructure, and project management among others. It is important to cover sustainability principles in depth in order to promote students experience in this field. It is important to observe that fresh graduate architects, civil engineers and building professionals will not have sufficient capacity and experience to design future sustainable, low energy homes to meet these requirements. This is due to the shortage of university curricula in this field. Some studies reflect a need to improve curricula to teach sustainability. This is reflected in the need for a guidance framework to support architects and civil engineers when designing future homes that meet environmental requirements, human needs and cultural challenges. Meanwhile, it is important to support curriculums in universities to include this field in depth, and provide postgraduate courses specialising in sustainability. Consequently, the proposed framework can be used as a reference for architects, civil engineers and building professionals. It will guide them in the selection of design strategies when designing friendly low energy homes for Saudi Arabian environments, and to meet cultural challenges.

This study is unique as it offers both comprehensive investigation and expert judgment, drawing on many individual design strategies informed by the literature and offering a comprehensive solution to suit the Saudi Arabian climate and context. Hence, the research methodology was designed to: (a) identify low carbon strategies and the techniques applicable to the Saudi Arabian climate and context, and (b) the development of a suitable methodological framework.

In light of this, the discussion will highlight four categories: (i) comparison with other frameworks; (ii) architectural design strategies in saudi arabian context, Environment and Culture; (iii) efficient design and strategies of house envelope design in Saudi Arabia and local suppliers influences; and (ix) on-site renewable energy in Saudi Arabia and individual investment.

### 6.3.1 Comparison With Other Frameworks

Similarities between current and related studies reference: (i) massing and spatial layout, (ii) fabric, and (iii) renewable energy strategies. This framework differs from other similar frameworks by including (a) specific design concepts, techniques and strategies drawn from the literature having been previously found suitable for hot climatic regions, (b) specific envelope design techniques and strategies for hot climatic conditions, also drawn from the literature, (c) on-site renewable energy solutions adapted to the Saudi context, and (d) in-depth consideration of local socio-cultural issues. Table 6.2 presents unique details of this study contrasted with two other frameworks (Hill and Bowen, 1997, Roufechaei et al., 2014)

Table 6.2 Unique Details Of This Study Contrasted With Two Other Frameworks

<table>
<tr><th>Category</th><th>Issues Covered</th><th>Similarities</th><th>Differences</th></tr>
<tr><td>Low Carbon Domestic Design Framework for sustainable Homes (The current study)</td><td>Thirteen Dimensions under the following categories: (a) Architectural Design, (b) House Envelope design, (c) On-site Renewable Energy, and (d) Socio-Cultural Issues.</td><td rowspan="3">(1) Low carbon home design.<br><br>(2) Focus on building form; fabric; and renewable energy strategies.<br><br>(3) Energy conservation in buildings and minimising CO2 emissions.</td><td>(1) Offers 79 specific design concepts, techniques and strategies to fit 4 dimensions.<br><br>(2) Discusses and promotes the best applicable designs related to external walls, roof, building shape, floor, glazing, HVAC in hot climatic regions.<br><br>(3) These design concepts and strategies are applicable to Saudi Arabia and hot climatic regions.<br><br>(4) These design strategies factor in local cultural challenges and availability of raw materials in the region.<br><br>(5) Mean point for each technique and strategy are provided to rank their importance.<br><br>(6) These design strategies are agreed to by qualified experts and can be employed as a reference when designing sustainable homes in hot climatic countries.</td></tr>
<tr><td>Sustainable construction: principles and a framework for attainment (Hill and Bowen, 1997).</td><td>(a) Biophysical, (b) Technical, (c) Social, and (d) Economic.</td><td>(1) Offers 26 Principles of sustainable construction.<br>(2) Discusses these principles to deliver sustainable developments.<br>(3) Proposes a multi-staged methodology for sustainable construction.</td></tr>
<tr><td>Energy-efficient design for sustainable housing development (Roufechaei et al., 2014).</td><td>(a) Architectural Design<br><br>(b) Mechanical<br><br>(c) Electrical</td><td>(1) Offers 22 energy efficiency parameters for low carbon house design and ranks their importance.<br><br>(2) Discusses these parameters in the local context.<br><br>(3) Identifies commonly referenced energy efficiency parameters.</td></tr>
</table>

This framework contributes to the body of knowledge by proposing a framework for the design of low energy homes, taking into account the hot climate of Saudi Arabia, and the specific cultural requirements in the country. This framework will address various aspects, such as architectural design (form), housing envelope design, construction materials (fabric), and on-site renewable energy solutions, and local socio-cultural issues. Architecturally, the proposed strategies cover building design, shading devices, heating, ventilation, air conditioning (HVAC), and massing. In terms of house envelope (design and construction materials used), the framework will cover building fabric design strategies, including the design of external walls, roofs, floors and external glazing. The low carbon domestic design framework will also suggest strategies for use with renewable energy resources. It will assist architects, civil engineers, building professionals and developers to design low energy buildings in Saudi Arabia. Furthermore, the framework is intended to be scalable and readily applicable to other countries in the Middle East region, with similar climates and cultural needs.

The applicability of design strategies differs between hot and cold climates. Generally, some strategies may be applicable to both, such as insulation within the house envelope, while other strategies are not. Table 6.3 presents the strategies applicable in hot climatic conditions, compared with cold climatic conditions.

**Table 6.3 Strategies Applicable In Hot Climatic Conditions, Compared With Cold Climatic Conditions**

| Strategy | For Saudi Arabian climate (Hot Climate) | For Cold climates conditions |
|---|---|---|
| ▪ South facing | ▪ Not recommended to avoid solar heat and reduce cooling demand | ▪ Recommended to gain solar heat and reduce heating demand |
| ▪ Use rectangular shape strategy | ▪ Recommended when taking into account the solar behaviour | ▪ Applicable for maintaining the width of the building, and accounting for solar radiation |
| ▪ Size of external windows | ▪ Recommended to keep the size of windows to a minimum to benefit from natural light for health purposes | ▪ Applicable for harvesting solar gain to reduce heating load |
| ▪ Shading device strategies | ▪ Recommended in terms of reducing cooling load | ▪ Not recommended as can increase the heating load |
| ▪ Sky lighting | ▪ Not recommended as can increase the cooling load | ▪ Applicable for the purposes of natural lighting and solar gain |
| ▪ Renewable energy | ▪ Recommended as a high amount of solar radiation | ▪ Recommended even when there is a shortage of solar radiation |

### 6.3.2 Architectural Design Strategies For Saudi Arabian Context, Environment And Culture

Architectural design concepts and strategies are based on local climate. It is well known that architectural design plays a significant role in a building's energy demands and evidence suggests that, buildings should be designed in accordance with the principles of optimally sustainable architecture (Al-Sallal et al., 2012, Cutler et al., 2008, Radhi, 2010, Taleb and Sharples, 2011). The most applicable design concepts and strategies for effectively conserving energy in the hot climate of Saudi Arabia have been investigated. As seen in the framework established in Figure 6.13 an efficient, a low carbon domestic design framework must identify features such as building shape, shading devices, HVAC and window design as shown below:

- *Massing and space layout:* In the regard to building mass and layout, it has been reported in chapter 5 that extra energy is used in rooms that are occupied most of the day, e.g. bedrooms and sitting rooms. In future, dwellings must be designed to reduce the areas given over to top floor rooms as suggested in the framework. Considering the level of use of rooms will facilitate minimisation of energy expenditure. Homes can be designed to allocate rooms that are occupied and operated over a long period to the ground floor, whereas rooms those are used for shorter periods (e.g. guest rooms) should be on the top floor. This will reduce the energy demand for air conditioning because rooms on the ground floor can be better insulated from the heat.
- *Landscaping and shading devices:* Firstly, failure to use efficient external landscaping in existing homes were identified and discussed in chapter 5 (Aldossary et al., 2014b, Aldossary et al., 2014a). As Saudi Arabia has a hot climate, shading devices and efficient landscaping can play a role in reducing energy demand for air conditioning. Trees in the external landscape provide shading, and have a proven impact on levels of cooling energy (Nikoofard et al., 2011, Akbari et al., 1997, Pandit and Laband, 2010). Planting an average of three trees per property can reduce annual and peak cooling energy use (Simpson and McPherson, 1998). In terms of shading devices, one of the problems for existing homes in Saudi Arabia is poorly

designed shading devices, which leads to a huge demand for air conditioning units (Aldossary et al., 2014b, Aldossary et al., 2014a). The shading techniques proposed in the framework are various, giving the architect the flexibility to design future homes with efficient shading devices, both externally and internally.

- *Heating Ventilation and Air-Conditionings:* Experts have already assessed HVAC design strategies in terms of their applicability to use in the Saudi Arabian climate. As Saudi Arabia has a hot climate natural ventilation is not always the best, energy saving option. Natural ventilation can be a suitable option in the south-western region, but using air conditioning systems is the most effective way of providing a cool internal environment. However, air conditioning can account for over 70% of the total energy consumption in existing buildings (Aldossary et al., 2014b, Aldossary et al., 2014a). Through investigation into the suitable techniques and strategies related to HVAC in the established framework, natural ventilation was found to be a very limited means to control use of air conditioning. Proposed natural ventilation strategies are applicable to the southern region and during some seasons of the year in hot and humid regions of Saudi Arabia.
- *Window design:* the strategies for designing windows have been considered and investigated in reference to the Saudi Arabian climate. External windows effect the amount of energy consumed in the home (Dussault et al., 2012). The size and location of windows is important in order to provide natural ventilation and natural light, whilst avoiding as much direct solar heat as possible (Huang and Wu, 2014). Solar light increases the temperature and consequently the air conditioning load. Meeting these requirements also depends on the location of the building, its orientation and wind direction (Huang et al., 2014). By conducting an investigation into different techniques and design strategies related to window designs for hot climates, many suitable strategies were identified. For example, a large window surface area is not efficient in a hot climate, as one of the techniques is to reduce the area and locate the windows along northern facades to avoid as much penetration from solar heat as possible.

### 6.3.3 Efficient Design And Strategies Of Housing Envelope Design In Saudi Arabia And Local Suppliers Influences

Suppliers of local construction materials in Saudi Arabia are important, as the availability and cost of raw materials plays a significant role in designing an efficient housing envelope. Investment in the construction materials industry depends on the efficacy of products in terms of resistance to individual elements of construction. Furthermore, the technique used to design external walls using insulating layers will increase the resistance in the final design of the housing envelope, and support the building's energy saving capacity (Bojic et al., 2002, Li and Chow, 2005, Fontanini et al., 2011, Dombaycı et al., 2006). Limited availability of efficient construction materials will limit the likelihood of constructing an efficient housing envelope for buildings. Currently, these is awareness of the need to develop a policy in Saudi Arabia to implement insulation as compulsory in external walls, for housing.

One of the problems and design weaknesses resulting in high energy consumption in existing domestic buildings in Saudi Arabia is poorly designed housing envelopes; this includes design of the external walls, roofs and windows (Aldossary et al., 2014b, Aldossary et al., 2014a). For example, the roof of a building can play a significant role in energy-saving in hot climatic conditions such as Saudi Arabia. Because the sun is directly overhead for a considerable part of the day, the roof of the building is likely to receive maximum exposure.

As the highest proportion of energy used in existing buildings in Saudi Arabia is consumed by air conditioning, it critical to design a building envelope that will function efficiently in countries with hot climates like Saudi Arabia, where temperatures can exceed 46°C (CDOS, 2008). These high temperatures result in high energy demands to run air conditioning and cool the internal environment in order to attain a satisfactory level of thermal comfort.

28 techniques and strategies have been proposed related to designing housing envelopes for the Saudi Arabian climate, availability of construction materials and raw materials. The proposed framework in this research can be used as a reference when designing a building envelope for Saudi Arabian housing; it involves multiple strategies taking into account raw materials, availability of construction materials.

In terms of the influence of external glazing in energy saving, an efficient design for the external glazing in windows can contribute to a reduction in energy consumption (Pisello et al., 2012, Gasparella et al., 2011, Jelle, 2013). As seen in the established framework, many techniques for designing external glazing for the hot climatic conditions in Saudi Arabia were investigated and approved in consultation with experts. As Saudi Arabia has a hot climate, double or triple glazing techniques are important design features when applied in conjunction with reducing the size of external glazed panels. It was found by the researcher at an earlier stage (chapter 5) (Aldossary et al., 2014b, Aldossary et al., 2014a), that one of the design weaknesses leading to high energy consumption in existing homes in Saudi Arabia is poorly designed, external, single glazing.

Due to the low price electricity tariff in the domestic sector in Saudi Arabia, there is little incentive to use efficient designs of house envelope, including additional external glazing.

### 6.3.4 On-Site Renewable Energy In Saudi Arabia And Individual Investment

Implementation of on-site renewable energy options is an important step to be taken when constructing future homes. In Saudi Arabia, these techniques are influenced by the cost of the technology, the availability of natural resources and strategies available to employ these techniques. Electricity in Saudi Arabia is subsidised by the government, and the renewable energy technologies are expensive for occupants, resulting in a preference for electricity supplied through burning fossil fuels.

In consultation with experts over three different rounds, some techniques and design strategies were established to establish procedures for on-site renewable energy use in Saudi Arabia. Saudi Arabia has a hot climate and is therefore able to generate abundant energy using solar radiation (Rehman et al., 2007). Saudi Arabia has ideal climate conditions for solar energy production (Hepbasli and Alsuhaibani, 2011). The availability of natural solar radiation in Saudi Arabia is variable, depending on the region, but can reach up to 2560 kWh/ m² per year (Rehman et al., 2007). This could be used to generate electricity for use in residential buildings. The amount of electricity generated from solar radiation can reach 15% of the available solar radiation in a location.

As found in the established framework; the uses of PV depend on site conditions, orientation of the building and urban designs oriented to the locations (lands). Hence, PV that is oriented to face south, used with the most efficient PV system is the best option in terms of energy generation. Orienting the PV to easterly and westerly positions is also an efficient strategy, because Saudi Arabia is located near to the equator and the sun is vertical during the day period. This strategy can be used as a second option depending on the site conditions.

According to the Ministry of the Municipality in Saudi Arabia, the area of land devoted to construction for residential purposes is 625m$^2$. This figure reflects a huge opportunity to install and invest in PV techniques in the domestic sector in Saudi Arabia. One of the problems is that whilst Saudi Arabia is ideally placed to benefit from renewable energy resources, existing domestic buildings make no use of this rich natural resource (Aldossary et al., 2014b, Aldossary et al., 2014a).

### 6.3.5 Employing Smart Building Technologies For Energy Conservation

Implementation of information and communication technologies in buildings is an important and effective strategy for energy saving and economic growth (Ishida, 2015). ICT can be applied in buildings in Saudi Arabia for energy management and conservation purposes. ICT can play a significant role in energy conservation if employed in sustainable homes in Saudi Arabia to manage energy conservation for lighting and air conditioning. The established framework has covered the importance of smart technologies, which control and manage energy behaviour in buildings. The framework offers architects and civil engineers or building professionals the opportunity to employ technologies for energy management and conservation. Firstly, the framework includes dividing the building into zones, wherein each zone has its own electricity information system. Each zone should have sensors to manage the air conditioning electricity needed where occupants are presented. As air conditioning will be the primary energy consumer, this smart system will lead to energy management and conservation. On the other hand, there is a framework included within the building management system (BMS) to oversee lighting and shading devices. This smart system will manage solar behaviour in the building, keeping energy consumption to a minimum. The designer will have multiple notions regarding using the ICT mentioned in the framework to design separate zones in the building and install technology for energy saving purposes. These technologies have been assessed as very important for inclusion in future sustainable homes in Saudi Arabia.

## 6.4 Summary

The Kingdom of Saudi Arabia has the opportunity and the resources to reduce energy consumption in domestic buildings, which currently consume over 50% of all electricity in the country (Electricity, 2010). To achieve this, a low carbon domestic design framework for sustainable homes for Saudi Arabia has been established, based on its climate, culture and locally sourced raw materials. This framework differs from other studies, as discussed earlier, as it takes into account local interests, environmental conditions, and socio-cultural issues. These design strategies and techniques have been investigated and approved through three rounds of experts' consultations. Many of these have been newly developed, and are not covered in previous studies, as they only emerged through the participation of experts. Consequently, this framework will act as a reference for developers, architects and civil engineers required to design low energy homes in Saudi Arabia to meet all local requirements, needs and environmental challenges.

It is extremely important to conduct an additional approach to implement the established framework, and to design different virtual housing prototypes according to the guidance provided by the framework. This will lead to, (a) identification of the levels of low energy consumption possible in the Saudi Arabian context and climate, and (b) validation of simulation software tools in the established framework. Hence, the following chapter will focus on and highlight this purpose.

Many developed countries have addressed energy conservation in the housing sector and established low energy consumption definition standards (in $kWh/m^2$) (Kirsten Engelund Thomsen, 2008, EU, 2009) based on their local needs and climatic conditions. The following chapter will focus on designing sustainable homes in Saudi Arabia based on an energy consumption definition system (in $kWh/m^2$) in line with the Saudi climate and cultural needs. The design of these low energy homes will be based on the framework established in this study to determine a minimum level of energy consumption that can realistically be achieved in Saudi Arabia. The findings will be compared with other international energy consumption definitions (in $kWh/m^2$), which will be used as a benchmark for the energy consumption definition for Saudi Arabia.

The final recommendation will incorporate a benefits prediction estimate based on economic and environmental factors.

# Chapter 7 : Establishing Domestic Low Energy Consumption Reference Levels For Saudi Arabia And The Wider Middle Eastern Region

## 7.1 Introduction

Saudi Arabia is renowned for its full reliance on fossil fuel energy and lack of an energy regulatory framework for its built environment. After establishing a low carbon domestic design framework for Saudi Arabia, it is essential to employ this framework and design multiple housing prototypes characterised by different design concepts, strategies to meet different cultural requirements. Therefore, this chapter will concentrate on identifying how low a level of energy consumption can be achieved in Saudi Arabia, and offer and validate different options for sustainable, low energy homes for Saudi Arabia.

As described in the methodology chapter 3 section 3.3.4 pp. 85-87, this chapter aims to: (a) establish levels of energy reduction, informed by leading standards (such as Passivhaus in Germany), that can be achieved taking into account the complex local socio-cultural context and environmental factors, and (b) propose a low energy reference definition with a view of encouraging energy retrofitting programs and enforcing domestic low carbon interventions. An energy simulation environment is employed to simulate and analyze energy consumption patterns of three proposed low carbon prototype houses that reflect current house typology and space layout in the country. The three proposed homes offer a reduction in energy consumption of up to 71.6%, compared with similar houses. Based on these findings, a domestic energy performance reference is proposed with energy consumption ranging between 77 $kWh/m^2$ and 98 $kWh/m^2$. Economic and environmental benefits are discussed as well as recommendations for enforcing low carbon design in the country and across the region.

Following this introduction, this chapter summarizes related research and low carbon definitions. This is followed by the underpinning methodology. The proposed low energy houses are then described, simulated, and analyzed. Finally, a proposal for low energy homes is discussed as well as the required energy policy framework.

## 7.2 Proposed Low Energy Houses For The Saudi Climate

Three different prototype low energy houses are proposed informed by earlier stages (Aldossary et al., 2014a, Aldossary et al., 2014b), and detailed below.

### 7.2.1 House Prototype1

This house is designed in line with current living space area of typical domestic homes in Saudi Arabia, as permitted by the planning consent authority (i.e. Ministry of municipality). The architectural drawings are illustrated in Figure 7.1, while Table 7.1 summarizes key design area figures.


**Figure 7.1 Layout Design Of House Prototype1**

**Table 7.1 Area Description Of House Prototype1**

| | | | |
|---|---|---|---|
| **Ground Floor Area** | 200.4 m² | **External Walls Area** | 487.7 m² |
| **First Floor Area** | 175.5 m² | **Total Windows Area** | 39 m² |
| **Second Floor Area** | 49.7 m² | **Total Volume of the House** | 1277.4 m3 |
| **Total House's Area** | 425.8 m² | **PV Area** | 60 m² |

This house can accommodate many family members and is designed with some energy conservation measures. The design can support all human activities and meets 100% of Saudi socio-cultural requirements (Aldossary et al., 2014a, Aldossary et al., 2014b).

#### *7.2.1.1 Architectural design techniques*

There is an abundant literature on low carbon interventions in the domestic sector (Anna-Maria, 2009, Al-Sallal et al., 2012, Chel and Tiwari, 2009, Cutler et al., 2008, Radhi, 2010, Taleb and Sharples, 2011). The design interventions of prototype1 draw on these techniques as summarized in the following techniques.

- ***Massing and space layout and windows design:*** The design aims to reduce the area of windows ensuring sufficient natural light, especially in south facing rooms (Li et al., 2002, Loutzenhiser et al., 2007, Yu and Chow, 2007). Also, the area of some rooms has been reduced, such as bedrooms, to lower energy demand, while still meeting socio-cultural requirements.
- ***Shading Device techniques:*** The first design intervention involved a sloping roof acting as a shading device on top of the House to protect the external roof from solar heat and reduce its temperature. Further shading devices were added on top of each window to prevent and reduce solar heat. Also, additional shading devices were added to the top of the surrounding walls that many people in Saudi Arabia construct for privacy purposes. Additional canopies were installed at the top of each storey with a 0.7m depth to provide additional shading.

#### *7.2.1.2 On-site renewable energy*

Solar panels (PV) were installed on the eastern and western orientation on no more than 35% of the total roof area. The electricity generated will be used to heat up the DHW, and support the air conditioning system, which accounts for 75% of energy consumption in a typical Saudi house (Aldossary et al., 2014a, Aldossary et al., 2014b).

#### *7.2.1.3 House envelope design*

As Saudi Arabia is hot and extreme environment for the majority of the year, it is important to design the envelope of the House with high thermal resistance to prevent or slow down heat transfer from the external to indoor environment. This will reduce the air conditioning load needed to achieve a satisfactory comfort level for occupants.

The approach used to measure the performance of the house envelope is through its thermal resistance (Desogus et al., 2011). ISO 9869 standards are normally followed for the in situ measurement of thermal resistance as well as the thermal transmittance of the house envelope (Peng and Wu, 2008, Al-Hadhrami and Ahmad, 2009, Al-Ajlan, 2006, Budaiwi et al., 2002). The thermal transmittance of the house envelope (U value in W/m²K) is be measured as (Nicolajsen, 2005):

$$U = \frac{1}{R_T},$$

where $R_T$ is the total thermal resistance (in $m^2$ K/W) of the construction materials used. This can be measured as:

$$R_T = R_{si} + R + R_{se},$$

$R_{si}$: is the internal thermal resistance of the house envelope

$R_{se}$: is the thermal resistance of external surface of the house envelope. The thermal resistance of the individual layer can be calculated by the theory below:

$$R = \frac{\lambda}{d},$$

where (λ) is the thermal conductivity (in W/m K) of the insulation materials used in the house envelope and (d) is the thickness (in meter) of each material used.

Table 7.2 below provides the details of the construction materials used for the envelope. The U-Value or R-Value is important to determine the efficiency of the house's envelope. The optimum design of House fabric (thermal insulation) plays a major role in reducing energy demand (Bojic et al., 2002, Dombaycı et al., 2006, Fontanini et al., 2011, Li and Chow, 2005). As illustrated in Table 7.2, the U-value for the external walls or roof was not more than 0.34 W/ $m^2$ k. A triple glazing system with a cavity filled with argon gas was used to reduce the transmission of direct-beam solar irradiation, reduce the heat gains from the ambient environment, and maintain adequate levels of daylighting (Askar et al., 2001, Tahmasebi et al., 2011)

**Table 7.2 Design Description Of The House Envelop For House Prototype1**

| House Envelope | Construction Materials Used | Thicknesses | U-Value W/ $m^2$ k | R-Value $m^2$ k/ W |
|---|---|---|---|---|
| **External Walls** | Vermiculite Insulating Brick, insulations materials and Brick worker | 45 cm | 0.345 | 2.72 |
| **Roof** | Roof tiles, insulations and concretes | 55 cm | 0.194 | 5.01 |
| **Floor** | Stone, concretes, insulations, sand and Mortar | 80 cm | 0.7 | 0.97 |
| **Internal partitions** | Plaster, Brickworks and Plaster | 13 cm | 1.6 | 0.33 |
| **Ceilings** | Cast Concrete (DENSE) and Carpet | 11 cm | 2.28 | 0.238 |
| **External Windows** | Triple Glazing with cavities filled with argon gas | | 1.72 (Glass only) | |

### 7.2.2 House Prototype2

This house was designed differently from house prototype1 in its detail and techniques as elaborated below.

#### *7.2.2.1 Architectural Design techniques*

***The massing and space layout*** involves smaller areas compared with a typical house in Saudi Arabia. The House is designed with a rectangular depth to avoid southern solar heat. The details of the architectural design are illustrated in Figure 7.2


**Figure 7.2 Layout Design Of House Prototype2**

Window areas are reduced to provide just required natural light. It is worth noting that the southern elevation does not have windows, eastern or western oriented windows are provided instead. Table 7.3 presents the area description of house prototype2.

**Table 7.3 Area Description Of House Prototype2**

| | | | |
|---|---|---|---|
| **Ground Floor Area** | 114.8 $m^2$ | **External Walls Area** | 357.5 $m^2$ |
| **First Floor Area** | 114.8 $m^2$ | **Total Windows Area** | 18.6 $m^2$ |
| **Second Floor Area** | 28 $m^2$ | **Total Volume of the House** | 772.9 m3 |
| **Total House's Area** | 257.6 $m^2$ | **PV Area** | 40 $m^2$ |

***Shading devices*** are installed in the house using (a) external shutters to prevent or slow solar heat transfer. An additional shading device is installed at the top of each window;

(b) as Saudi Houses have an external surrounding wall for privacy purposes, an external device is installed on the top of the wall at a height of 7 meters; and (c) the sloping roof technique is used to prevent solar heat reaching the ceilings in the top floor rooms. Each external window is equipped with an internal shutter. In addition, the shutters are insulated and painted in a dark colour.

#### *7.2.2.2 On-site renewable energy*

Similar to house prototype1, prototype 2 involves the use of PV panels. The sloping roof, to the east and west, provides the ideal location for PV panels. The total area of the roof is 114.8 $m^2$, 40 $m^2$ of which is allocated to PV panels. The energy generated will then be used to operate the air conditioning and heat up the DHW (Aldossary et al., 2014a, Aldossary et al., 2014b).

#### *7.2.2.3 House envelope design*

The house envelope uses a double skin for the external walls. For the basement floor, several layers of stone and efficient construction materials are selected. Triple glazing with argon gas is used in the external windows to increase their R-Value. Table 7.4 presents the house envelope design for the house, including material specification.

**Table 7.4 Design Description Of The House Envelop For House Prototype2**

| House Envelope | Construction Materials Used | Thicknesses | U-Value W/ m² k | R-Value m² k/ W |
|---|---|---|---|---|
| **External Walls** | Brickwork, EPS slab insulation, polyurethane board, and inner Brickwork | 30 cm | 0.257 | 3.70 |
| **Roof** | Roof felt, Felt insulation material, mineral fibre slab, cast Concrete (Light Weight), Cavity Insulation (ASHRAE) and ceiling mortar | 46.5 cm | 0.237 | 4 |
| **Floor** | Stone, Cast Concrete (Light Weight), Sand, dens EPS Slab Insulation and clay tiles | 76 cm | 0.104 | 8.4 |
| **Internal partitions** | Plaster and Brickworks and Plaster | 13 cm | 1.6 | 0.33 |
| **Ceilings** | Cast Concrete (DENSE), Mortar and Carpet | 11 cm | 2.28 | 0.238 |
| **External Windows** | Triple Glazing with cavities filled with argon gas | | 1.72 (Glass only) | |

### 7.2.3 House Prototype3

This housing design is intended for a small family, keeping the living area to a minimum. The design is dramatically different from both the current housing style in Saudi Arabia and the other house types designed in this study. The socio-cultural aspects are overlooked (a western style space layout is used) to demonstrate optimal energy reduction.

#### *7.2.3.1 Architectural Design techniques*

***The massing and space layout*** is smaller compared to the two previous prototypes. It is laid out simply over two floors with a sloping roof to allow for an attic space. The layout plan is shown in Figure 7.3.

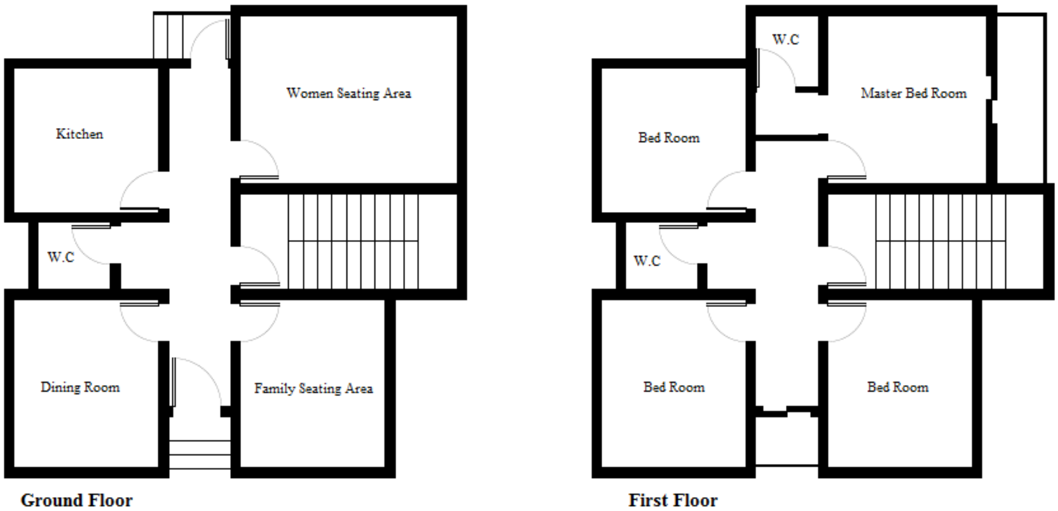



**Figure 7.3 Layout Design Of House Prototype3**

This house is oriented in a northerly direction to avoid the impact of solar heat as much as possible. The attic contains two rectangular windows on the east and west elevation to allow natural ventilation at night. These will be closed during the day to create a cooler space between the sloped roof and the ceiling on the top floor. The sizes of the rooms are minimized to avoid extra space, which neither adds value nor reduces energy consumption, while still meeting the occupants' needs. As with the other house prototypes, this design avoids south-facing windows and reduces their area to 0.75m².
Table 7.5 shows the details of the area description of house prototype3

**Table 7.5 Area Description Of House Prototype3**

| | | | |
|---|---|---|---|
| **Ground Floor Area** | 67.7 $m^2$ | **External Walls Area** | 229.3 $m^2$ |
| **First Floor Area** | 64.6 $m^2$ | **Total Windows Area** | 12.4$m^2$ |
| **Attic Area** | 64.6 $m^2$ | **Total Volume of the House** | 397.1 m3 |
| **Total House's Area** | 132.3 $m^2$ | **PV Area** | 30 $m^2$ |

The Facade brace technique is used as a shading solution. This allows natural ventilation on the southern façade to reduce air conditioning load. Additional shading devices are installed on top of each window to prevent solar radiation reaching the external glazing. Additional external shutters are installed for each window to prevent solar heat reaching the windows during the hottest periods of the day. To maximize insulation, dark insulated curtains are installed.

#### *7.2.3.2 On-site renewable energy techniques used*

This house is smaller than the two other prototypes, and/or typical homes in Saudi Arabia. It provides about 30 m² of roof space on which PV is installed. The generated energy will be used to contribute to the cooling system (air conditioning) energy needs and domestic hot water DWH.

#### *7.2.3.3 House envelope design*

Table 7.6 illustrates the final design of the housing envelope. In order for the U-values to be kept to a minimum, the external walls and the double skin insulating wall are designed with multiple layers and adequate thickness.

**Table 7.6 Design Description Of The House Envelop For House Prototype3**

| House Envelope | Construction Materials Used | Thicknesses | U-Value W/ m² k | R-Value m² k/ W |
|---|---|---|---|---|
| **External Walls** | Insulating Bricks, Polystyrene insulation, additional insulating Bricks, Dens EPS Slab Insulation and final insulating Bricks | 40 cm | 0.2021 | 4.7778 |
| **Roof** | Clay Tile, fibre slab, sand, Vermiculite Aggregate concrete and Gypsum / Plaster Board - HF-E1 (ASHRAE) | 45 cm | 0.2126 | 4.4203 |
| **Floor** | gravel- Based Soil, cast Concrete (DENSE), sand, Cork Tiles, Carpet and pad (ASHRAE) | 67 cm | 0.6244 | 1.1525 |
| **Internal partitions** | Plaster, Brickworks and Plaster | 13 cm | 1.6896 | 0.3319 |
| **Ceilings** | Cast Concrete (DENSE) and Synthetic Carpet | 11 cm | 2.28 | 0.2381 |
| **External Windows** | Triple Glazing with cavities filled with argon gas | | 1.72 (Glass only) | |

## 7.3 Simulation, Analysis And Validation

The three proposed house prototypes are assumed to be low energy structures, compared with current homes in Saudi Arabia. This assumption, however, must be tested and validated by comparing their energy consumption and $CO_2$ emission rates to those of current Saudi homes. These compared levels will be measured using international definitions for low energy housing systems expressed in kWh/m². Each house design will be tested and simulated using IES-VE.

A BIM (Building Information Model) was created for each house prototype based on (a) architectural design, (b) selected construction materials, (c) on-site renewable energy techniques used, and (d) user profiles for an average Saudi family (Aldossary et al., 2014a, Aldossary et al., 2014b). The housing types will be compared to each other based on their area, energy consumption, and $CO_2$ emissions. This comparative analysis will outline the benefits and advantages of each house prototype.

### 7.3.1 Energy Consumption

The aim of this stage is to identify what level of low energy consumption can be achieved in Saudi Arabia, and what low energy consumption definition standards (in kWh/m²) are realistic and applicable to all regions of the country to establish an official standards policy for Saudi Arabia in a line with some developed countries in EU (Kirsten Engelund Thomsen, 2008, EU, 2009).The local climate plays a significant role in the energy consumption of buildings, and consequently, IES-VE simulation results vary according to the local climatic conditions. The findings in chapter 5 describe the energy consumption of different regions with hot climates; i.e. hot arid climates, hot humid climates, and hot arid climates with mountainous topography (see Table 7.7). Each type of climate creates unique conditions that influence the energy requirements for cooling and heating. The energy consumption is known to be lower in the mountainous region than others regions; therefore, to attain realistic standards (in kWh/m²) that can be applied countrywide, the measurements will be taken in one of the hottest most aggressive environment in Saudi Arabia and cold in wenter period, where the highest level of energy is required.

**Table 7.7 Different Climatic Cinditions In Saudi Arabia (CDOS, 2008)**

| | | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Hot Arid Climate (Riyadh City)** | **Max. Temperature** | 28 | 31 | 37.8 | 39.6 | 44.5 | 45.6 | 46.8 | 46 | 45 | 38 | 30.4 | 27 |
| | **Min. Temperature** | -5 | -0.7 | 7 | 14 | 18.9 | 22.7 | 24.4 | 23 | 21.8 | 16.6 | 10.7 | -1.2 |
| | **Relative humidity** | 44 | 25 | 13 | 19 | 15 | 9 | 10 | 12 | 16 | 26 | 49 | 34 |
| **Hot Humid Climate (Jeddah City)** | **Max Temperature** | 32 | 35 | 39 | 42 | 42 | 48 | 45 | 41.5 | 42 | 43 | 38 | 36.5 |
| | **Min Temperature** | 13 | 15.4 | 18 | 19 | 20 | 23.4 | 24.8 | 25 | 23.8 | 20 | 20 | 17 |
| | **Relative humidity** | 59 | 56 | 60 | 58 | 56 | 58 | 49 | 52 | 66 | 61 | 65 | 51 |
| **Hot Arid Climates with mountainous topography (Al-Baha City)** | **Max Temperature** | 28.3 | 28.5 | 31.8 | 34 | 37 | 37 | 38 | 37 | 37.6 | 32 | 28.6 | 29 |
| | **Min Temperature** | 2.4 | 3 | 9 | 16 | 16 | 19 | 21 | 20 | 19.6 | 13 | 11 | 3 |
| | **Relative humidity** | 66 | 41 | 28 | 37 | 38 | 28 | 23 | 23 | 28 | 33 | 55 | 44 |

As expected, energy consumption for the three prototypes (based on IES-VE simulation results) is relatively low, but with different reduction levels. In this section, the energy consumption patterns for the three houses will be presented, in terms of: (a) annual energy consumption, (b) monthly energy consumption, (c) energy profiling (i.e. nature of consuming devices), (d) comparison of the energy consumption with international low energy housing definitions, and (e) annual $CO_2$ emissions rates. Moreover, the results will be compared to current energy consumption rates, as found in chapter 5.

#### *7.3.1.1 Annual Energy Consumption*

Figure 7.4 presents the total annual energy consumption in kWh for the three proposed low energy housing designs.

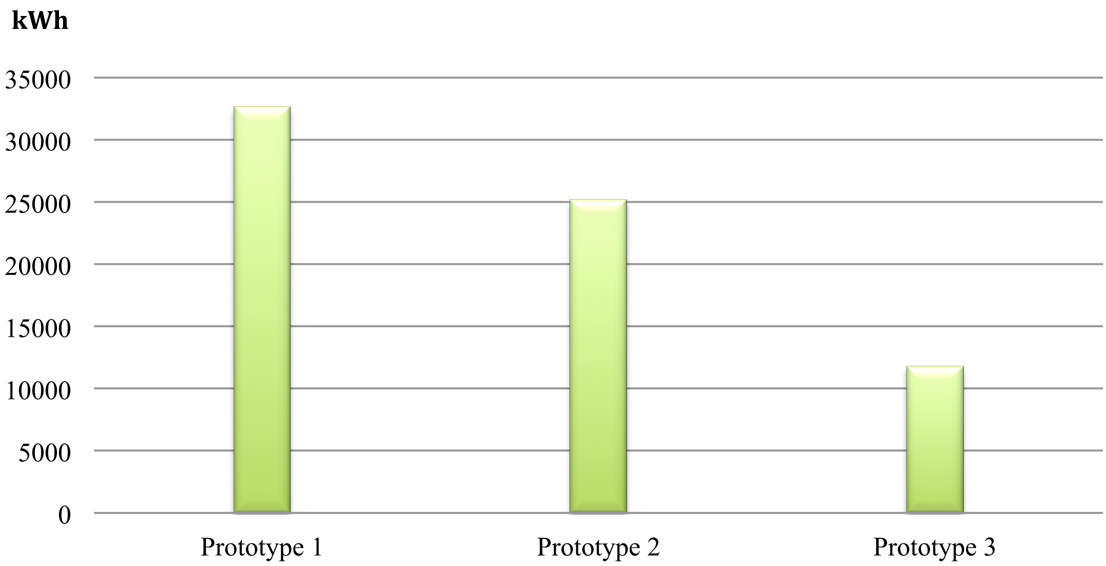



**Figure 7.4 Annual Energy Consumption For The Three House Prototypes (IES-VE Simulation Results)**

These energy consumption levels are lower than existing homes in Saudi Arabia as established in (Aldossary et al., 2014a, Aldossary et al., 2014b) where average energy consumption for a typical house in Saudi Arabia can be up to 60.000 kWh per year, depending on the type of climatic conditions (hot arid climate, hot humid climate, or hot arid mountainous conditions). Therefore, it can be stated that:

- Energy consumption of house prototype1 is up to 63% of the average energy consumption of similar existing homes, which represents a future potential reduction of 37%.
- Energy consumption of house prototype2 is up to 41.6% of an average similar house, representing a reduction of 58.4% in energy consumption, when compared with typical homes in Saudi Arabia.
- Prototype3 consumes only 28.3% of the energy consumed by a typical house in Saudi Arabia. Therefore, its construction would deliver up to a 71.7% reduction in energy consumption compared with similar homes in Saudi Arabia.

Figure 7.4 points out that house prototype3 has the highest performance in terms of low energy consumption due to its smaller size, efficient design form, and high quality fabric.

#### *7.3.1.2 Monthly Energy Consumption*

Figure 7.5 presents the monthly energy consumption levels for all three housing prototypes. Generally, these Houses require mechanical systems for cooling and energy consumption with a high demand during the summer months.

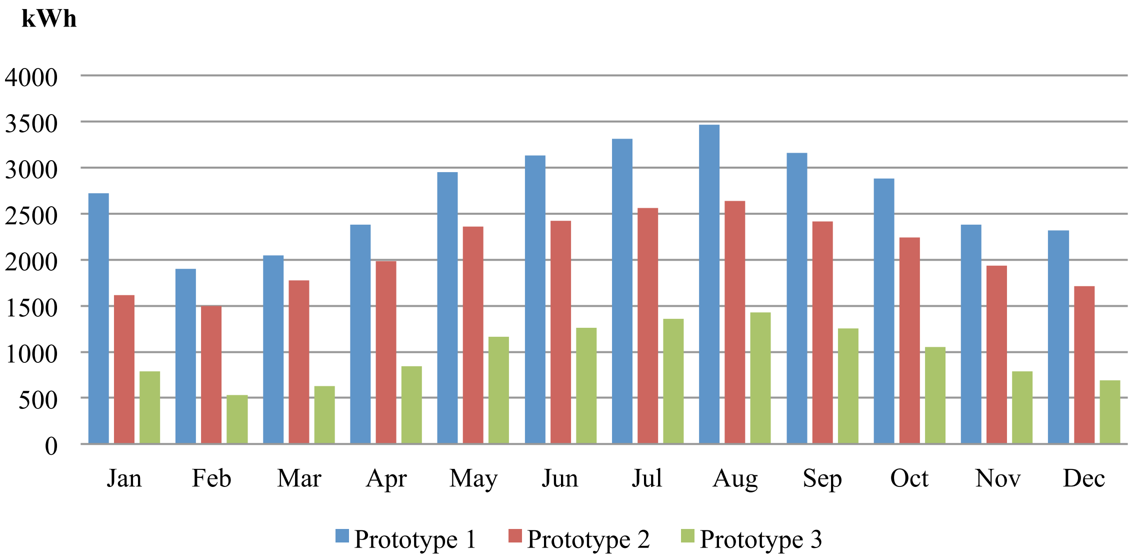
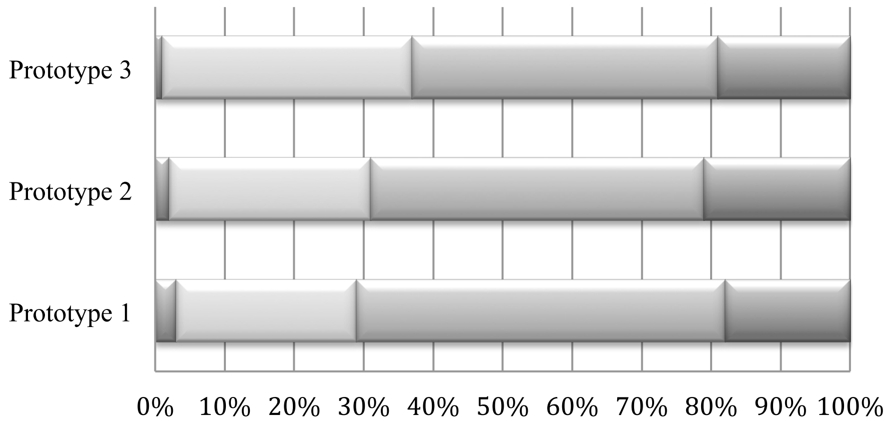



**Figure 7.5 Monthly Energy Consumption For The Three Housing Designs**

#### *7.3.1.3 Energy Consumption Profiling*

As identified in previous stage (Aldossary et al., 2014a, Aldossary et al., 2014b), the cooling system (air conditioning) accounts for the bulk of energy consumption (i.e. over 80%) in existing houses in Saudi Arabia. As mentioned previously, cooling systems in existing houses in Saudi Arabia usually consume about 70% and can sometimes consume over 80%. The IES-VE simulation results show that the percentage of energy used by the cooling system has been reduced and no longer presents a problem. Finally, the energy used for lighting, equipment or energy pumps, is not affected by the design of the form and fabric of the House. Form and fabric can affect energy use only for cooling or heating systems, in accordance with the local climate. Lighting energy can be reduced through the use of natural lighting and the efficient design of windows in each room, and by keeping the size and area of the windows to a minimum to prevent increasing the load on the cooling system. Energy profiling of each prototype is summarized in Figure 7.6.




| | Prototype 1 | Prototype 2 | Prototype 3 |
|---|---|---|---|
| Heating system | 3% | 2% | 1% |
| cooling system (Chillers energy, Ap Sys heat rej fans/pumps energy) | 26% | 29% | 36% |
| Ap Sys aux + DHW/solar pumps energy | 53% | 48% | 44% |
| Lightings and Equipments | 18% | 21% | 19% |

**Figure 7.6 Energy Profiling For The Three Housing Designs**

### 7.3.2 Benchmarking Results With International Low Energy Houses Definitions

This section presents a scale upon which to measure the level of low energy consumption for the three housing designs informed by international official low energy housing definitions and standards. As mentioned earlier, there is no energy consumption standard for sustainable houses in the Middle East or the Gulf Cooperation Council (GCC) countries with which to compare the results. Conversely, many developed countries have established a standard of energy use based on their needs and local climate conditions. Consequently, this study benchmarks the findings and the energy patterns for the housing designs according to these international low energy consumption standards. Figure 7.7 compares annual energy consumption in kWh/m² for the three houses with a selection of international sustainable low energy standards.

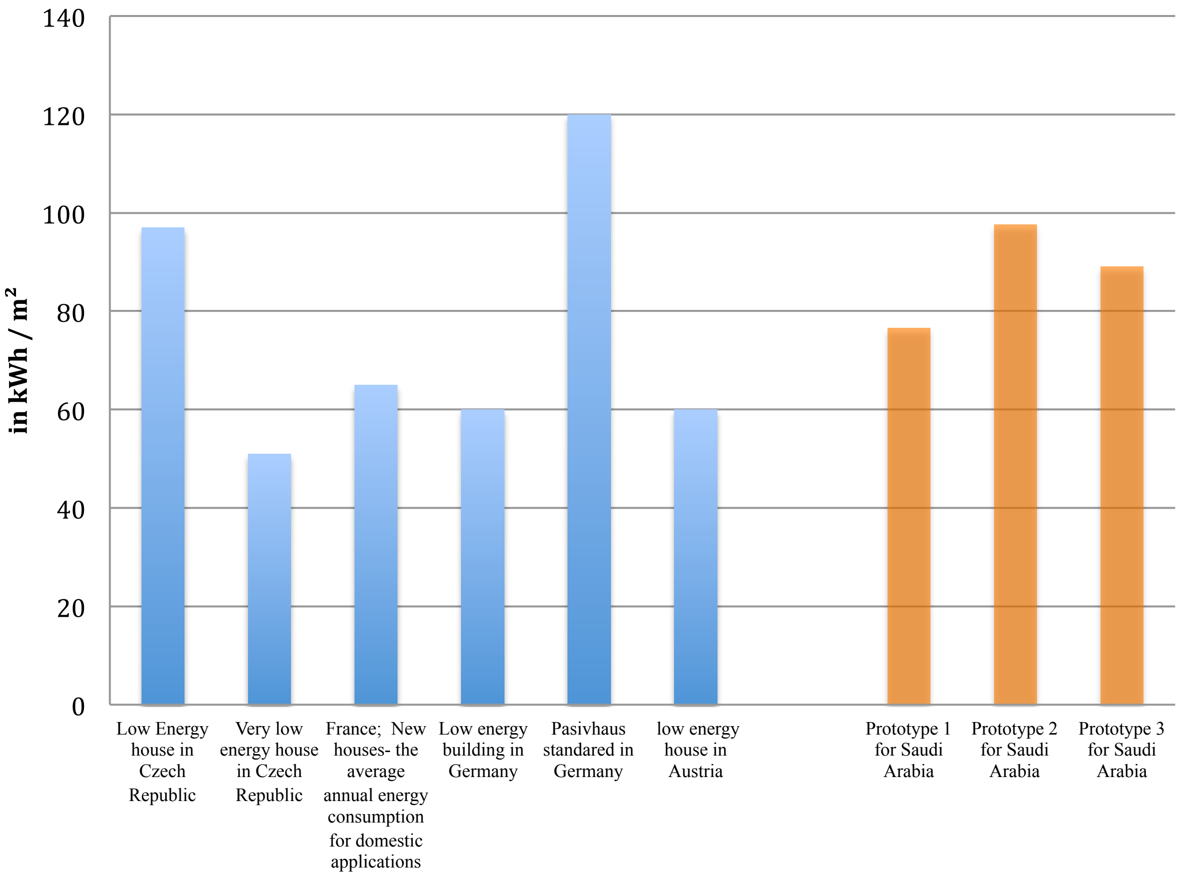



**Figure 7.7 Benchmarking Energy Consumption In kWh / m² With International Standards**

As illustrated in Figure 7.7 all three housing designs achieve lower energy consumption when compared with the low energy house in the Czech Republic and the Pasivhaus standard in Germany. It is worth noting that other standards demand even lower energy consumption than achieved; i.e. the very low energy house in the Czech Republic or low energy House in Germany and France. Some other developed countries are still working to improve energy consumption and aim at achieving zero energy consumption by 2016; such as is the case for England and Wales in the UK.

### 7.3.3 $CO_2$ Emission Rates

Figure 7.8 illustrates annual $CO_2$ emission rates for each housing design. These rates range between 1700 and 6000 kg/year and as such are considerably lower than the $CO_2$ emission rates of typical existing homes in Saudi Arabia that reach up to 42570kg/year (Aldossary et al., 2014b, Aldossary et al., 2014a). Clearly, these results represent a success in reducing $CO_2$ emissions and subsequently protecting the environment.

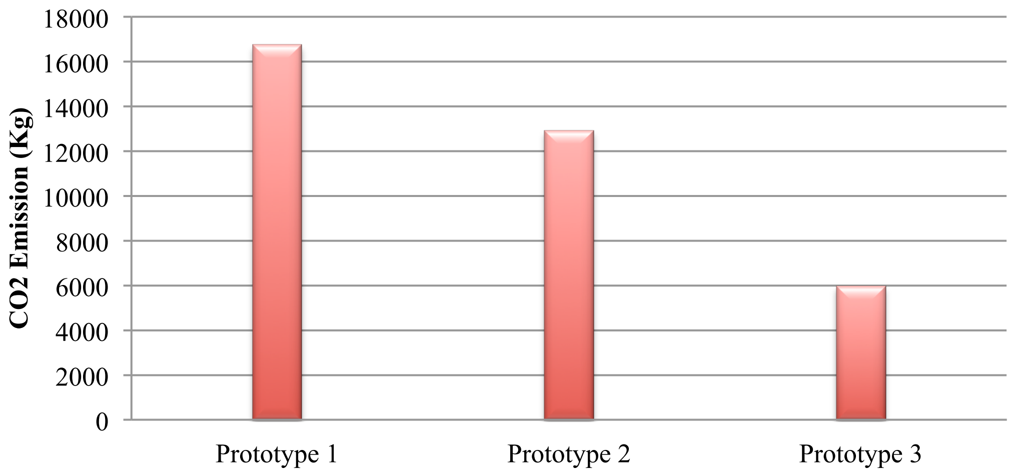



**Figure 7.8 Annual CO2 Emission Rates (Kg) For The Three Housing Designs**

According to Doukas et al (2006) , the average CO2 emission rate per capita for the analyzed 25 European countries is about 2.5 tons per year (Doukas et al., 2006). Thus, all three types of houses can be said to be close to, or lower than the average $CO_2$ emission rates per capita in these 25 EU countries. Figure 7.9 illustrates the annual $CO_2$ emission rates per capita, by dividing the total $CO_2$ emissions by the size of the average family (number of occupants) in Saudi Arabia. It can be seen that house prototype3 produces the lowest $CO_2$ emission rates, while house Prototype1 produces the highest. Yet in all three houses, both $CO_2$ emissions and energy consumption remain lower than rates in existing houses in the country.

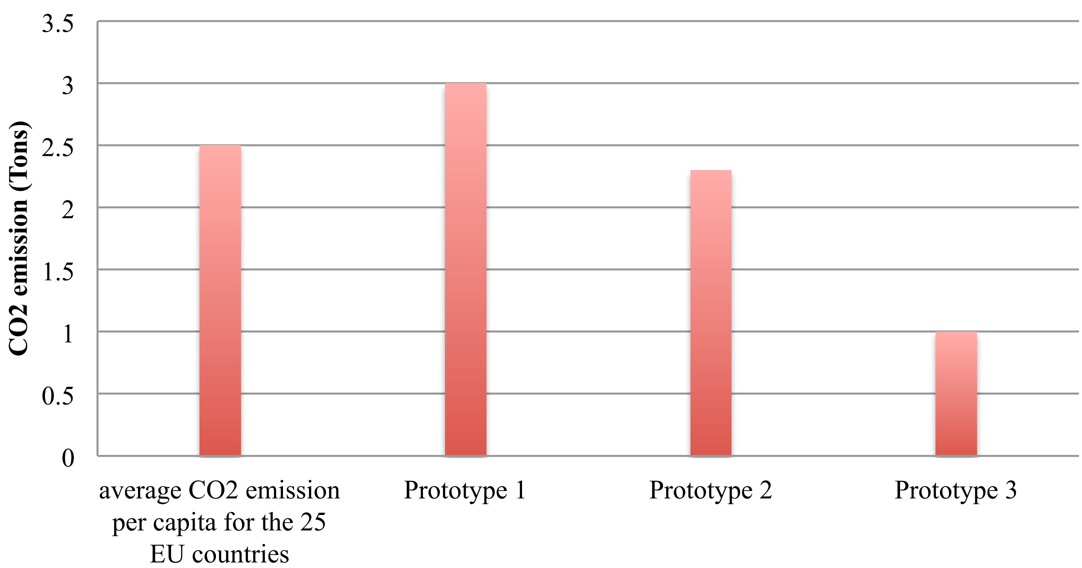



**Figure 7.9 Annual $CO_2$ Emission Rates (Per Capita) For The Three Housing Designs Compared With 25 EU Countries**

### 7.3.4 Thermal Comfort Dimension

To attain thermal comfort in countries with hot climates energy is required to operate air conditioning systems. There are many environmental factors that affect thermal comfort, including air temperature, radiant temperature, humidity level and air velocity.

In hot climatic conditions, air conditioning systems are employed to cool down indoor spaces to attain a satisfactory level of thermal comfort. This accounts for over 70% of the energy consumed, as identified in chapter 5. However, means to minimise energy demand for air conditioning have been implemented while still attaining a satisfactory level of thermal comfort. Several studies have discussed how to reduce energy consumption for air conditioning. Zaki et al. (2012) (Zaki et al., 2012) advocate the use of passive architectural design principles in terraced houses, with a view to promoting natural thermal comfort for residents. They have adapted the design strategies of passive architecture to lessen demand for mechanical cooling. They achieved major energy reduction (approximately 83%) through the use of passive architectural design principles.

For the three housing design prototypes, an HVAC system is important in ensuring thermal comfort. The system will provide energy for air conditioning, as Saudi Arabia has a hot and aggressive climate, and energy for air condition is essential to meet the thermal comfort of occupants. The architectural design strategies for each prototype and house envelope design were considered. The aim was to keep (a) energy consumption to a minimum, and (b) provide acceptable levels of thermal comfort. According to the simulation results for the three prototypes, this was achieved.

The efficient design of the house envelope slows down external hot air as it passes through the walls, and architectural principles can be used to limit the effect of solar heat by providing shading devices. The level of thermal comfort differs from person, to other but the average is range between 18 and 25 °C. The external temperature in Saudi Arabia is above this range, thus air conditioning is essential to achieve thermal comfort.

## 7.4 Low Energy Consumption Definition Standard For Saudi Arabia

This section focuses on the establishment of a low carbon energy consumption reference for Saudi Arabia that factors in climate and socio-cultural constraints. The economic and environmental benefits of the adoption of such a reference system are discussed.

The Saudi government subsidizes energy use in the residential sector. Moreover, occupants do not pay for actual energy consumption as the cost of consumed energy is subsidized (Alyousef and Stevens, 2011). Ideally, the Saudi government should regulate energy price based on predicted annual energy use, balancing demand and offer, as is the case in Western countries.

According to the Ministry of Municipality in Saudi Arabia, planning consent is granted if the following requirements are met:

(a) The area should not be more than 60% of the site area allocated in the deed.
(b) The distance between the House periphery and the property line should not be less than 2m, to maintain privacy.
(c) Only two floors should be completed, and no more than 25% of the roof should be built.
(d) The distance between the main elevation of the House and the street should not be less than 4m.
(e) The distance between the side entrance (if allocated) and the boundary / property line should not be less than 3m.
(f) Some other general requirements related to the property approval.

Outward appearance and privacy are the determining factors for home design in Saudi Arabia. There is no incentive or planning requirements to encourage / force engineering consultants to design low energy houses, and there is no related building energy legislation in place. The Energy Performance Building Directive (Directive 2002/91/EC) introduced the compulsory energy certification of buildings in the EU. This is now a key reference to monitor and reduce energy consumption in the European building stock. A similar directive should be enforced in Saudi Arabia and the wider region requiring a domestic energy performance between 77 kWh/m² and 98 kWh/m², as established in this study. Moreover, this should be enforced at the planning stage.

These measures will have a real impact on the domestic sector which currently accounts for over 50% of the energy use in Saudi Arabia. Moreover, the total energy consumed by the residential sector in the Kingdom in 2010 was about 108,627 GWH (Electricity, 2010). If the proposed prototypes are adopted, energy savings between 40% and 75% can be achieved. Figure 7.10 illustrates the benefits of each of the houses designed in this study.

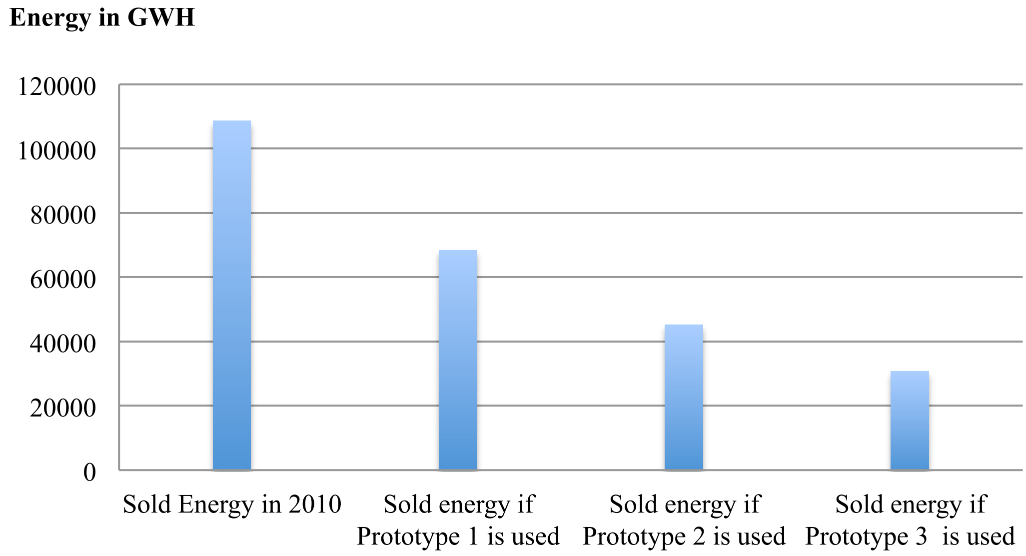



**Figure 7.10 Prediction Energy Saving Strategically Through Implementing These Houses In Saudi Arabia**

According to the ministry of housing, there is a rising demand for housing over the next 10 years (Ministry of Housing, 2014). The demands for future housing will require the erection of 214,433 residential units (Ministry of Housing, 2014). This figure reflects a serious challenge and illustrates the importance of designing low energy homes in the future. At the same time, this figure reflects the potential scale and benefits that could be achieved by implementing low carbon interventions.

According to (Ruiz Romero et al., 2012, Alnatheer, 2005), recent successes in adopting on-site renewables can be attributed to public financial incentives. Adapting the energy industry to allow more efficient and sustainable electricity production increases the importance of distributed generation from renewable sources (e.g. PV) (Richter, 2013). Incentivising and implementing the retrofitting solutions that have been proposed in this study for existing houses and flats across Saudi Arabia will require complementary measures to be put in place. Policies could be developed and enforced to encourage home owners to retrofit their dwellings. A dramatic reduction in energy use will not only save on the cost of electricity, but will also significantly reduce the amount of $CO_2$ emissions and will enhance the international profile of the country with significant social, economic and environmental benefits (Kneifel, 2010, Chel et al., 2009).

Future deployment and enforcement is essential when adopting low energy housing in the construction industry in Saudi Arabia. It is of importance to create a funded institute to manage energy conservation in the construction industry in Saudi Arabia (e.g. business model). The research has provided comprehensive tools for future deployment to establish a roadmap for implementation to create a green clean and sustainable environment. Information has been provided concerning a low carbon domestic design framework for sustainable homes, which supports the architect and civil engineers when designing sustainable homes in Saudi Arabia. For future enforcement, introducing BIM principals and employing a framework within the industry will assist in achieving low energy homes. This can be implemented by establishing a business model in the construction industry in Saudi Arabia. Certainly lower levels of energy consumption can be achieved. Figures for this can be based on the suggested energy consumption standard system (from 77 to 98 kWh/m²). Hence, the outputs of this study will genuinely support future deployment.

### 7.4.1 Renewable Energy Investment And Cost Effect Analysis

Renewable energy technology has been suggested for all three prototypes. Saudi Arabia has a high amount of solar energy, which can be utilised on-site, as renewable energy for domestic purposes. Photovoltaic PV technology is flexible and popular for personal consumption. Hence, PV technology has been used for each prototype in all three options based on the roof area of each prototype. The output from energy generation depends on the local availability of renewable energy. Saudi Arabia's climate is seen as a negative; however, it does provide access to high amounts of solar radiation. The cost of electricity differs from country to country, and according to the local economy. Thus, benchmarking, using a renewable energy analysis, has been performed with other countries, to highlights the benefits of energy saving, including cost savings. Table 7.8 presents, (a) the available solar radiation in Saudi Arabia, London, Paris, and Berlin (Celik et al., 2009), (b) the electricity that can be generated, and (c) potential cost savings. The cost of electricity is shown in the table for each country in Euros with the potential energy generation of PV technology implemented. Table 7.8 below illustrates the benchmarking for potential energy and cost savings for Saudi Arabia compared with other international cities.

**Table 7.8 Benchmarking Of Potential Energy And Cost Saving For Saudi Arabia Compared With International Cities**

| | Local Solar Radiation in kWh/ $m^2$ | Electricity can be generated in kWh /$m^2$ | Electricity can be generated for 50 $m^2$ in kWh | Cost of electricity per 100 kWh in € | Potential annual cost saving electricity for 50 $m^2$ in € |
|---|---|---|---|---|---|
| **Saudi Arabia (Riyadh)** | 2560 | 384 | 19200 | 1 | 192 |
| **United Kingdom (London)** | 894.2 | 134.13 | 6706.5 | 8.77 | 588.1 |
| **France (Paris)** | 1138 | 170.7 | 8535 | 11.94 | 1019 |
| **Germany (Berlin)** | 1025 | 153.75 | 7687.5 | 17.85 | 1372.2 |

It can be seen that, there is huge potential saving of energy cost by employing renewable energy generation. It is important to note that, the government subsidised electricity price is presented in this table for Saudi Arabia (all energy products are subsidised by the Saudi government for its people). Hence, the actual saving of electricity would be greater than suggested by the table if the support for electricity were removed. On the other hand, rising awareness when implementing renewable energy technology is important and will encourage investment in technology and renewable energy in the Saudi construction market. In chapter 4, it was highlighted that there is shortage of renewable energy technologies in Saudi Arabia (Aldossary et al., 2015), while employing this technology in domestic sector in Saudi Arabia will lead to a greener environment and a reduction in $CO_2$ emissions.

### 7.4.2 Employing Simulation Software Tools In Decision Making

For successful management of energy consumption and conservation, it is important to employ software simulation tools to predict energy consumption by a particular residential project. Simulation software tools will predict energy consumption rates, the efficiency of the final design (form and fabric) and offer a final report illustrating energy performance. At present, many software tools for modelling and simulation are available in the industry, such as IES-VE, EnergyPlus and others. These software tools will support the architect and civil engineer throughout the design process and in decision making concerning the final design, according to the predicted energy consumption and the efficiency of final design (form and fabric). On the other hand, the software tools will provide flexibility to modify the design in order to determine the most efficient option, based on site conditions, client requirements and budget. The final report and a digital copy of the project will assist decision makers in governmental institutes, such as the Ministry of Electricity and the Ministry of the Municipality to double check the final design against energy consumption, as predicted using the simulation tools. Hence, decision makers in governmental institutes can choose to approve or reject a project according to the established energy conservation requirements.

### 7.4.3 Business Model Application And CAP Value

It is important to implement a business model in Saudi Arabia in order to manage energy consumption and conservation. Many developed countries have investigated the importance of a business model as it fits their context, that is their local environment conditions and needs. For example, in Russia, according to (Paiho et al., 2015), business models were identified from the literature and it was concluded that they were mostly “meant for some energy production solutions” (Paiho et al., 2015). This can relate to both large scale and limited improvement and better energy performance in the building’s sector (Paiho et al., 2015). They emphasised that the two basic business models distinguished and offered useful energy conservation to the end user in the domestic sector (Paiho et al., 2015). Hence, establishing a business model will lead the energy industry in Saudi Arabia to prioritise and manage the sustainable construction industry. Many research institutes in Saudi Arabia established and confirmed the importance of energy conservation, but the business model can take the leading budget officially from the related ministry to manage energy conservation in Saudi Arabia.

An established business model could assist in the employment of a low carbon domestic design framework in this study to design a future housing in Saudi Arabia.

Consequently, this business model will manage and link responsibilities among related governmental institutes who are responsible in the construction industry (e.g. ministry of municipality, ministry of electricity and ministry of housing). This business model can raise public awareness, and implement a framework to enable engineering consultants to design sustainable low energy homes in Saudi Arabia.

On the other hand, building information modelling (BIM) manages the construction design process including the energy consumption process. It is important to employ building information modelling (BIM) in the construction industry in Saudi Arabia to link the responsibilities of building professionals and offer an efficient design using multiple design tools such as; revit building design software, IES-VE and others. Building management modelling in the construction industry can assist residential projects in the design stages and focus on the energy consumption perspective to predict the energy demand and $CO_2$ emission rates. Hence, this technology in the business model will provide flexibility when managing process during the design stage process.

The responsibilities of the business model are: (a) to review the individual final design of future homes, (b) approve the design in terms of energy consumption to meet the occupants' needs and environmental issues, (c) offers training for engineering and building professionals to use new technologies when building information modelling BIM, energy simulation tools and sustainability industry, and (d) provide awareness for the public emphasising the importance of energy saving in homes. The business model can include the Capitalisation rate (CAP value) to compare different housing investments. Low energy housing in the future should provide an advantage in terms of investment, as there are many benefits to this type of housing over typical high energy consumption housing in Saudi Arabia. Hence, this sets the CAP value with the business model to manage energy conservation in the housing industry, which will lead to a better environment and economy in Saudi Arabia.

## 7.5 Summary

The chapter introduces three prototype low energy houses factoring in the Saudi Arabian climate, culture and occupants' needs. The energy performance of these prototypes has been validated using the IES-VE energy simulation environment to establish the extent of energy reduction compared with current homes. Based on this analysis low carbon energy consumption targets for Saudi Arabia are proposed, ranging between 77 kWh/m² and 98 kWh/m². This level of energy consumption compares favourably with international definitions of energy consumption in Germany, Czech Republic and France, as elaborated earlier. The economic and environmental benefits of the adoption of such a reference system have also been discussed.

# Chapter 8 : Research Conclusion

## 8.1 Introduction

The primary aim of this research was to design low carbon housing options that meet the cultural challenges of the Saudi Arabian context. In addition, considering the hot aggressive climate, the secondary research aim was to establish a standard for realistic energy consumption to be measured in $kWh/m^2$. Seven research questions were established and presented in the introduction chapter, each contributing to guiding the researcher to meet the research objectives. This chapter concludes the work by presenting the research findings as answers to the research questions, which provided the starting point of the research. Moreover, this chapter shares the conclusions reached during the research process and illustrates the final product and contribution to the body of knowledge. The limitations encountered by the researcher during the research process are also summarised. The chapter offers recommendations to the Saudi construction industry, including guidelines for the relevant government sectors and developers, and additional recommendations for future researchers working in this field. Finally, this chapter will present future work to be undertaken by the researcher. Therefore, this chapter is divided into four main sections: (i) Research Conclusion; (ii) Research limitations; (iii) Recommendations; and (iv) Future work for the researcher.

## 8.2 Research Conclusion

The first point to make is that the researcher has successfully met the main aims proposed for the study. The main aim of this research was to establish designs for sustainable, low carbon domestic buildings in Saudi Arabia, taking into account the local hot climate conditions, the architectural context, people’s needs and their cultural requirements. Chapter six details the low carbon domestic design framework that was developed for low energy homes appropriate for the Saudi Arabian climate, context and culture. Moreover, the study has also established low energy consumption reference levels for Saudi Arabia, which are applicable throughout the wider Middle Eastern region. The suggested low energy consumption level is given in $kWh/m^2$, to facilitate the control and management of energy uses in the Saudi Arabian context, in a manner similar to that utilised in some developed countries (the details of this appear in chapter 7). The remainder of this section discusses the conclusions following completion of the four stages of the research in reference to each of the research questions.

**Research Question One:**

***What is the average energy consumption in typical existing homes in Saudi Arabia and what level of $CO_2$ emissions result from operating typical homes in Saudi Arabia?***

Chapter 5 shows the energy consumption patterns for domestic buildings in Saudi Arabia to answer this question. Eighteen existing and occupied dwellings, located in the three distinct climatic zones (hot arid, hot humid, and hot arid mountainous region) of Saudi Arabia were selected for modelling and energy simulations. The investigation included exploration of energy consumption patterns for each individual case, the efficiency of the building mass and envelope design, and occupant behaviours. The data included official layout plans from the ministry of municipality that showed the architectural design, building mass and house envelope design of the selected dwellings. Official electricity utility bills were consulted to determine actual energy use during the year under investigation. The electricity bills showed no consistent energy consumption across the utilised sample. Instead, they indicated energy consumptions that varied according to local climatic conditions, building envelope and mass, and occupant behaviour; e.g. hot humid climates (cases) resulted in the highest annual energy consumption of to 84356 kWh. The bulk of the energy consumed in houses in Saudi Arabia (up to 86%) is for cooling systems, meanwhile, about 22% is consumed for DHW.

**Research Question Two:**

***What are the design weaknesses related to the architectural design (form) and house envelope design (fabric) that cause high energy consumption in existing domestic buildings in Saudi Arabia?***

Many design weakness were identified and discussed in chapter 5. These weaknesses were investigated at site visits, and through individual modelling and investigation of 18 existing dwellings across Saudi Arabia using IES-VE software tools for BIM (Building Information Modelling). Key design weaknesses can be summarised as: (i) Poor design of housing envelope with low resistance (R-Values) and high U-Values. Such building envelopes, then, result in heat transferring from the external hot environment to indoors, requiring extra energy to operate cooling systems to attain a satisfactory level of thermal comfort. (ii) Poor architectural design with respect to both the orientation and location of rooms and their area and volume. Spacious rooms, for example, are often placed in the top floor and are directly exposed to solar heat increasing the energy expenditure for operating air condition units. At the same time, lack of shading devices and external landscaping further exacerbates the problem. (iii) Absence of the exploitation of on-site renewable energy, such as solar energy and non-use of PV to generate electricity, although Saudi Arabia has a wealth of solar heat (up to 2560 kWh/ m² per year (Rehman et al., 2007).

The issues raised here were taken into account when developing a low carbon domestic design framework for future sustainable homes in the Saudi Arabian climate, context and culture.

**Research Question Three:**

***What are the factors impacting on energy consumption and what are the cultural factors that affect house design in Saudi Arabia and result in high energy consumption?***

Chapter 4 investigated the factors impacting on the energy consumption and identified the socio-cultural factors that influence architectural design and result in high-energy consumption. A key cultural factor is that gender mixing is not allowed in Saudi culture for reasons of religion and tradition, thus, each home has two separate rooms for guests one for males and another one for females. Allocating different spaces to guests increases energy demand for lighting, cooling, etc. The number and location of dining areas also required extra energy. In Saudi Arabia, the overall size of dwellings reflects one’s social status, and so people are motivated to increase the number of rooms in their dwellings. Having more bedrooms than is required by the occupants is another factor resulting in a high demand for energy; moreover, spacious bedrooms serve a small number of occupants and require energy to operate each bedroom with lighting, cooling and equipment.

**Research Question Four:**

***What is the public perception of sustainable, low energy buildings in Saudi Arabia and the socio-cultural blockers that inhibit sustainable, low energy homes in Saudi Arabia?***

This question was answered by investigating public perceptions in chapter 4, as well as the willingness of the public to adopt changes to ensure the future of sustainable low energy homes in Saudi Arabia. First, it was observed that there is a lack of understanding about the concept and importance of low energy homes. Some people have background knowledge about the concept, but others (42%) do not. The majority of respondents observed that if the public lacks awareness about sustainable homes, then the government and decision makers in the industry must take steps to overcome it. The lack of sustainable products and markets in Saudi Arabia also emerged as an obstacle to the adoption of sustainable practices in Saudi Arabia. PV products, for example, are in short supply in the country. Despite this lack of knowledge, once informed, most of the respondents (over 90%) expressed a willingness to move towards sustainable homes in the future in order to save energy and minimise $CO_2$ emissions.

Some socio-cultural barriers were identified as limiting the potential for sustainable homes in Saudi Arabia. These were, allocation of two large guest rooms on the ground floor. The public are unwilling to choose a home with a single guest room to be shared by both genders in order to save energy, due to their beliefs. Moreover, the size of a house is associated with a corresponding social status, and it is an issue the public seems to be reluctant to compromise on.

**Research Question Five:**

***What is the level of energy efficiency (based on energy efficient design) that can be achieved for housing in Saudi Arabia when compared with developed countries?***

This question was answered in depth in chapter 7. The level that can be considered to denote low energy consumption in Saudi Arabia was validated in reference to multiple house prototypes. IES-VE simulation software tools were employed to assess the efficiency of three, proposed housing prototypes in reference to their architectural design (form) and housing envelope design (fabric). The simulations identified 77 kWh/m^2 as the lowest energy level that is achievable in Saudi Arabia, taking into account the hot climate and socio-cultural requirements. This figure was then benchmarked against international low energy consumption recommendations in Germany, France and the Czech Republic. The proposed level for low energy consumption in Saudi Arabia is lower than that in the Czech Republic, and the Pasivhaus standard in Germany, but currently, international energy consumption standards demand even lower energy consumption than that achieved; this is exemplified by very low energy houses in the Czech Republic and the low energy houses discussed in Germany and France.

**Research Question Six:**

***How can the construction of existing homes be altered and retrofitted in order to reduce energy consumption?***

This question was answered in chapter 5 with some proposals for suitable retrofitting strategies to improve the energy efficiency of existing housing. The investigation and analysis of 18 dwellings across Saudi Arabia to discover energy consumption patterns, also brought forth possible strategies for sustainable solutions. Retrofitting solutions can be adopted for existing housing and save energy consumption by up to 37%. These retrofitting strategies are flexible and easy to install in an existing dwelling, and can be summarised as: (i) replacing the external single glazing with an efficient triple glazing with argon gas between each pane;(ii) installing efficient shading devices horizontally on the top of each window, as well as external shutters and additional vertical shading devices around the building to provide shade during the day; and (iii) installing on-site renewable energy (PV) at the top of the building to generate electricity from the natural solar radiation in Saudi Arabia, which produces up to 280 kWh/m².

These three strategies were tested and validated by applying IES-VE simulation tools to the 18 dwellings studied across Saudi Arabia. The cases were then re-modelled individually according to the three solution strategies, as described in chapter 5. It was calculated that, the retrofitting solutions offer energy reductions of between 15% and 37% compared to the original energy consumption.

**Research Question Seven:**

***In future, how can sustainable, low energy housing be designed in Saudi Arabia, and which framework methodology can be used? And what economic and environmental benefits can be achieved by establishing low energy housing in Saudi Arabia?***

This question was answered in chapter 6, which established a low carbon domestic design framework for the Saudi Arabian climate, context and cultural requirements. This framework was established and developed through consultations with experts (40 experts) using the Delphi technique (Keeney et al., 2001, Landeta and Barrutia, 2011, Al-Saleh, 2009, Chan et al., 2001, Geist, 2010) in three rounds of consultations. This framework contributes to the body of knowledge and supports architects, civil engineers and building's professional in designing future entirely sustainable homes in Saudi Arabia. Moreover, this framework was validated in chapter 7, which proposed three housing prototypes. The final designs for the prototype houses were characterised as low energy homes compared with the existing housing identified in chapter 5.

Meanwhile, economic and environmental benefits were displayed in chapter 7, which reveals the consequence of implementing each of the three prototypes implemented officially in Saudi Arabia. It was found that, a huge economic benefit could be achieved by reducing petroleum consumption for domestic purposes (based on 2010 figures), enabling sales of petroleum elsewhere at greater profit.

## 8.3 Research Limitations

The researcher faced multiple limitations during the research process; these are summarised as follows.

**Limitation One:**

Part of the research required an online public survey to specify the overarching research questions. The main limitation was related to the reliance on computer-based participants (i.e. those with access to the Internet). According to Central Department Of Statistics & Information in Saudi Arabia, In 2013, 5.6% of Saudi Arabians were illiterate and had no access to the Internet. Therefore, the study involved only educated people in Saudi Arabia, who in 2013 comprised 94.4% of the population, according to the central Department of Statistics and Information. In terms of Internet access in

Saudi Arabia, use by young people is more frequent than by older people (Simsim, 2011), 11.1% of Saudis do not use email services, and 15.6% of the public do not use any Internet service (Simsim, 2011). In addition, according to the Ministry of Electricity in Saudi Arabia, some villages in suburban areas across Saudi Arabia are not covered by the national electricity grid, relying on local energy sources; thus, these people were not included in the study. Nevertheless, despite these limitations the study reached the majority of towns and cities across Saudi Arabia.

**Limitation Two:**

During part of the research site visits were required, as was the modelling of domestic buildings to investigate energy consumption patterns, identify design weaknesses in the form and fabric of the buildings and propose solutions to reduce energy consumption. It was difficult to include a high enough number of cases in this study given the complex Saudi socio-cultural environment and barriers to accessing household utility/electricity bills. The researcher was only able to access utility bills with prior authorisation from the property owners due to the sensitive information they contain. Therefore, the researcher had to obtain the data from the occupants of respective properties, who had in turn obtained them from the Ministry of Municipality (official plans) and Ministry of Electricity (electricity bills). The researcher acknowledges this as a limitation of the research, and encourages follow-on studies that extend the sample size to encompass a greater number of properties.

**Limitation Three:**

The final stage in the research required the design of low energy homes to satisfy the needs of the Saudi Arabian climate, context and culture. In addition, at this stage it was essential to investigate and validate low energy consumption, prove levels of achievement and establish energy consumption standards for Saudi Arabia. It is well known that constructing a physical model to validate energy consumption would deliver a more realistic evaluation, but that the timeframe, scale and cost were limitations, and the researcher had to use software simulation tools to determine final energy consumption.

## 8.4 Recommendations

The research offers a framework on which to base the design of a sustainable clean environment for residential buildings in hot climates in general and in the Saudi Arabian context in particular. On the basis of the findings of this study, recommendations covering, the construction industry in Saudi Arabia (developers and decision makers), clients and consumers, and future researchers, can be made. The following general recommendations are tailored to suit both future and existing domestic buildings in Saudi Arabia, and to meet the requirement to achieve low carbon energy targets.

### 8.4.1 Recommendations For Researchers

Key recommendations for researchers are as follows:

i. Embodied energy to construct sustainable homes in Saudi Arabia will require a different approach in this study. Hence, it is recommended that future researchers focus on embodied energy when manufacturing materials for buildings in Saudi Arabia, keeping the embodied energy and $CO_2$ emissions to a minimum.
ii. To investigate and research the field of embodied energy use for construction in the building sector, including the residential, commercial and governmental sector and narrow down to conserve the embodied energy demand for these buildings in the future;
iii. To research and evaluate the mechanisms that would enable appropriate management and implementation of the principles of sustainable building design in Saudi Arabia, taking into account official and cultural blockers;
iv. Develop and manufacture new construction materials with low thermal transmission (U-value) from local raw materials in Saudi Arabia;
v. Develop and manufacture PV systems that deliver high performance energy generation utilising natural resources and estimate the economic payback;
vi. Investigate the energy consumption patterns at the two holy mosques in Makah and Medina including Hajj period in Saudi Arabia, which is the only place in the world that receives enormous numbers of pilgrims in a short period; and
vii. Develop a framework to manage and conserve energy at Hajj facilities, including the transport energy, electricity and $CO_2$ emissions in the two holy mosques in Makah and Medina.

### 8.4.2 Recommendations For Decision Makers

Key recommendations for the decision makers are as follows:

i. Revise regulations and policies in the construction industry to build low energy homes in Saudi Arabia and ensure economic and environmental benefits;
ii. Revise and update conditions for approving housing permits to add energy consumption requirements to the building design;
iii. Approve the established energy consumption standards for Saudi Arabia to control energy use by future domestic buildings;
iv. Promote simple solutions for energy retrofitting of existing domestic housing stock;
v. Invest in natural resources in Saudi Arabia, such as solar radiation, for future use across all sectors;
vi. Raise public awareness regarding the level of energy consumption in the domestic sector, and educate the public on the importance of reducing energy consumption in both the environment and the economy;
vii. Establish organisations in Saudi Arabia to study and approve plans for future homes, taking into account the proposed low carbon techniques and strategies; and
viii. Establish stringent policies and regulations to enforce the low carbon design of domestic buildings.

### 8.4.3 Recommendations For The Construction Industry (Developers, Engineering Consultants And Decision Makers)

Key recommendations for the construction industry workers are as follows:

i. It is beneficial, during the design and construction stages of a domestic building, to incorporate efficient, high resistance insulation within the house envelope (wall, roof, doors, windows and floor) in order to prevent or slow down heat in its passage from the external environment;
ii. Use efficient insulated double or triple glazing to prevent direct heat from the sun entering interior spaces;
iii. Use a passive sustainable design, including an efficient building shape, and minimise building size as much as possible;

iv. Design efficient external shading devices and use landscaping to cool the surrounding environment and to assist in the reduction of energy consumption for air conditioning systems;

v. Use onsite energy generation systems, such as PV, to generate electricity from natural resources and to reduce energy consumption from the grid, thereby reducing $CO_2$ emissions;

vi. Raise public awareness to educate people about how to reduce personal energy consumption;

vii. Revise the policies in place to force households to reduce consumption by increasing the price of electricity if it exceeds predicted limits; and

viii. Establish an energy consumption code for residential buildings in Saudi Arabia.

## 8.5 Future Work

It is well known that, researchers build upon each other's work. New studies are built on the foundations of former studies and so it is useful to highlight the potential of this research to stimulate future studies.

**Firstly:** in light of the findings in this research and the current situation in Saudi Arabia in terms of energy consumption in domestic buildings, there is a need for a transition process, leading from the current situation to a clean friendly sustainable and low energy environment. This process requires a timescale and roadmap during which to increase awareness. Hence, the researcher's future aim is to design strategies to ensure the implementation of a low carbon domestic design framework within the Saudi housing sector. The project will require an in depth study and analysis of the policies and regulations of property managers in the construction sector, and of construction permits obtained by organisations associated with the construction industry in Saudi Arabia; such as, the ministry of the municipality, the ministry of housing, the ministry of electricity, and engineering consultants and construction companies. Moreover, this will require amendments to current policies on electricity use and housing design, in accordance with the findings of the current research, which has (a) developed a low carbon domestic design framework, and (b) suggested a system to measure low energy consumption in $kWh/m^2$. The roadmap will focus on three transition phases to implement the solutions and to manage and control energy savings in Saudi Arabia. The first phase will target the capital and larger cities in Saudi Arabia; implementation will focus on towns and suburbs in the following phases.

**Secondly:** The researcher is a lecturer at Al-Baha University in the southern region of Saudi Arabia, so future work will focus on studies in energy and building development in Al-Baha city in the cooperation with the Al-Baha municipality. These studies will focus on estimating energy demand in all sectors in the region, and aim to discover how to develop a framework, in conjunction with the municipality, officially to conserve energy consumption in all sectors, including, agriculture, transportation, governmental, commercial and industrial sectors in the Al-Baha region. The output of this future study will lead those in the other regions in Saudi Arabia to plan and establish a roadmap to achieve sustainability in all sectors in Saudi Arabia. This proposal has already been discussed with the mayor of the Municipality (Eng. Mohammed Mobark Almjally) who has the power to deliver the findings to the decision makers in Saudi Arabia.

**Thirdly:** Future work could focus on research and analysis of new and inventive architectural interventions that could improve a building’s energy performance. The adoption of passive cooling systems, for example, could prove particularly beneficial for Saudi Arabia and the broader region. Such an approach, however, would require site specific studies taking into consideration local climates and weather patterns. The results could include innovative solutions that satisfy sustainability principles while at the some time incorporating local materials and possibly even indigenous building methods. The outcome from such research, furthermore, could provide additional design options.

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# APPENDIX

# APPENDIX A - Public Survey Questionnaire

**مقدمة**

السلام عليكم ورحمة الله وبركاته
نظراً لزيادة الإهتمام بالمباني المستدامة المرشدة للطاقة الكهربائية في العالم ولحاجة المملكة العربية السعودية إلى مباني مستدامة مرشدة للطاقة, أفيدكم بأني طالب مرحلة الدكتوراة في تخصص الهندسة المعمارية والبناء في كلية الهندسة جامعة كارديف, بريطانيا. موضوع الدراسة يتضمن التصميم المعماري والتشييد المستدام المرشدة للطاقة للمباني السكنية في المملكة العربية السعودية. [illegible] الرسالة عن كيفية تصميم المباني السكنية معمارياً وتشييدياً على أن تكون مرشدة للطاقة. يتطلب ذلك الى دراسة الوضع الراهن في المملكة العربية السعودية لتقييم المشكلة الحالية ومعرفة تصورات ووجهات نظر المجتمع السعودي في هذا المجال. الهدف الرئيسي من هذا الإستبيان هو تحليل أولاً): تصورات المجتمع السعودي عن المباني السكنية المستدامة المرشدة للطاقة, (ثانياً): أسباب الهدر في) إستهلاك الطاقة في المباني السكنية الحالية. (ثالثاً): تأثير العادات والتقاليد الإسلامية في المجتمع السعودي على التصميم المعماري للمباني السكنية. هذة الدراسة فقط لغرض التحصيل العلمي ودراسة إيجاد حلول وبدائل علمية وليس لأي غرض آخر. يستغرق الإجابة على هذا الإستبيان حوالي 10 دقائق من وقتك

**جهدك ووقتك يهمنا وإجابتك على هذا الإستبيان في محل التقدير والفائدة العلمية**

Dear Sir/Madam
I am doing my PhD at Cardiff University in the UK, my research being in the field of Sustainable Architectural Design and Construction. I am conducting a study of the current situation with regard to building design and energy consumption patterns in Saudi Arabia. The main purpose of this information will be to analyse (a) public perception of sustainable dwellings; (b) the reasons for high energy consumption, including behaviour, forms and fabrics; and (c) the influence of Islamic culture on occupants' behaviour and architectural style in Saudi Arabia. This research is undertaken solely for academic reasons, NOT for any other. It will take you only 10 minutes to answer the questions on this questionnaire.

Your effort and time are highly appreciated.

1. المعلومات الشخصية (الإجابة إختيارية)؟
Please type your demographic information (optional)?

الاسم (Name): ____

البريد الإلكتروني (Email Address): ____

*2. في أي مدينة او محافظة تعيش في المملكة العربية السعودية؟ (In which city do you live in Kingdom of Saudi Arabia?)

____

*3. ماهو جنسك؟
What is your gender?

○ ذكر (Male)

○ أنثى (Female)

○ لا أرغب القول (Rather not to say)

*4. كم عمرك ؟
what is your age?

- من 18 الى 34 سنة (from 18 - 34)
- من 35 الى 49 سنة (from 35- 49)
- من 50 الى 64 سنة (from 50- 64)
- أكثر من 64 سنة (more than 64)

*5. المستوى التعليمي؟
What is your qualification?

- ثانوية عامة (High school)
- درجة الدبلوم (Diploma)
- درجة الباكالوريوس (A bachelor's Degree)
- درجة الماجستير (Master's Degree)
- درجة الدكتوراة (Ph.D)

القسم الأول/ أجب عن الأسئلة التالية المتعلقة عن منزلك الذي تعيش فيه

Section (1) Please answer the following general questions about your dwelling

*6. مانوع المنزل الذي تعيش فيه؟
What type of dwelling do you live in?

- فيلا دور واحد (one-storey house)
- فيلا دورين (two-storey house)
- فيلا دبلكس (semi detached house)
- شقة (flat)

7. ماهو عمر منزلك تقريباً؟
What is the age of your dwelling?

- Under 5 years (أقل من 5 سنوات)
- 5 –10 years (من 5 -10 سنوات)
- 11 – 20 years (من 11 -20 سنة)
- Over 20 years (اكثر من 20 سنة)

*8. ماهي مساحة منزلك تقريباً؟
What is the area of your dwelling?

- Less than 100 $m^2$ (أقل من 100 متر مربع)
- From 100 to 300 $m^2$ (من 100 الى 300 متر مربع)
- From 301 to 600 $m^2$ (من 301 الى 600 متر مربع)
- From 601 to 1000 $m^2$ (من 601 الى 1000 متر مربع)
- Over 1000 $m^2$ (اكثر من 1000 متر مربع)

*9. كم عدد الأفراد الذين يعيشون في منزلك؟
How many people living in the dwelling?

- 1
- 2
- 3
- 4
- 5
- 6
- 7 and over (اكثر من 7 أفراد)

*10. كم عدد غرف النوم في منزلك؟
How many bedrooms does it have?

- 1
- 2
- 3
- 4
- 5
- أكثر من 5 (More than 5)

*11. كم عدد غرف الطعام في منزلك؟
How many dining rooms in your dwelling?

- 1
- 2
- 3
- أكثر من 3 (More than 3)

*12. كم عدد دورات المياه في منزلك؟
How many toilets are there in your dwelling?

- 1
- 2
- 3
- 4
- 5
- أكثر من 5 (More than 5)

*13. هل لديك غرف ضيافة منفصلة للنساء عن الرجال في منزلك ؟
Do you have separate guest rooms for males and females in your dwelling?

- نعم (Yes)
- لا (No)

*14. كم عدد غرف الضيافة المخصصة للرجال؟
How many guest rooms for males do you have in your dwelling?

- 1
- 2
- أكثر من 2 (more than 2)

15. كم عدد غرف الضيافة المخصصة للنساء؟ الرجاء عدم الاختيار اذا كانت غرفة ضيافة الرجال تسخدم للنساء
How many guest rooms for females do you have in your dwelling? (Do not select any answer if you use the male guest rooms for both genders.)

- 1
- 2
- أكثر من 2 (more than 2)

القسم الثاني/ أجب عن الأسئلة التالية المتعلقة بإستهلاك الطاقة في منزلك وأنظ...

Section (2)Please answer the following questions about energy consumption patterns and cooling systems used in your dwelling

*16. هل تعرف تكاليف إستهلاك الطاقة الكهربائية الشهرية في منزلك بالريال السعودي؟
Do you know the cost of annual energy consumption in Saudi Riyal in your dwelling?

- نعم (Yes)
- لا (No)

17. إذا كانت الإجابة نعم, ماهي قيمة إستهلاك الكهرباء الشهرية في منزلك تقريباً بالريال السعودي؟
If yes, what is the cost of energy consumption in Saudi Riyal per month?

- Less than 500 Saudi Riyal / month (أقل من 500 ريال في الشهر)
- From 500 to 1000 Saudi Riyal / month (من 500 الى 1000ريال في الشهر)
- From 1001 to 2000 Saudi Riyal / month (من 1001 الى 2000 ريال في الشهر)
- More than 2000 Saudi Riyal / month (أكثر من 2000 ريال في الشهر)

*18. كم متوسط المدة الزمنية التي يتواجد بعض الأسرة في المنزل أو يكون المنزل مأهولاً بالسكان خلال اليوم بإستثناء أوقات النوم؟
How long is your dwelling occupied per day on avarage (not including hours of sleep)?

- 3 hours per day (ثلاث ساعات في اليوم)
- 3-6 hours per day (من 3 الى 6 ساعات في اليوم)
- 6-10 hours per day (من 6 الى 10 ساعات في اليوم)
- Over 10 hours per day (أكثر من 10 ساعات في اليوم)

*19. ماهو نوع نظام التكييف المستخدمة في منزلك (يمكنك إختيار أكثر من إجابة)؟
What type of cooling system do you use in your dwelling? (You can give more than one answer.)

- أجهزة التكييف (Air-conditioning)
- التهوية الطبيعية بإستخدام فتح الشبابيك والأبواب (Natural ventilation)
- مراوح سقف أو مراوح صحراوية (Ceiling fans, Standing fans...etc)

*20. ماهو نوع نظام التدفئة المستخدمة في منزلك (يمكنك إختيار اكثر من إجابة)؟
What is used the heating system in your dwelling? (You can give more than one answer)

- أجهزة التكييف (Air conditions)
- الدفايات الكهربائية (Electrical radiators)
- دفايات الزيت الكهربائية (Oil filled radiator)
- لا نحتاج دفايات (We do not need radiators)

21. إذا كنت تستخدم أجهزة التكييف ماهي جودة إحكام تسريب الهواء الخارجي في منزلك؟ (if you are using air conditioning how would you assess the quality of the air tightness in your dowelling?.)

- ○ رديء (Poor)
- ○ مقبول (Fair)
- ○ جيد (Good)

*22. في أي غرف تستخدم أجهزة التكييف؟
Where do you use air-conditioning?

- ○ في كل الغرف (in all rooms)
- ○ في غالبية الغرف (in the majority of rooms)
- ○ في بعض الغرف (in some rooms)

*23. كم مدة إستخدام أجهزة التكييف في منزلك خصوصاً في فصل الصيف؟
For how long is the air conditioning used per day (especially in summer time) ?

- ○ Less than 5 hours a day (أقل من 5 ساعات في اليوم)
- ○ From 5 to 10 hours a day (من 5 الى 10 ساعات في اليوم)
- ○ From 10 to 15 hours a day (من 10الى 15 ساعة في اليوم)
- ○ From 15 to 20 hours a day (من 15الى 20 ساعة في اليوم)
- ○ Over 20 hours a day (أكثر من 20 ساعة في اليوم)

24. إذا كنت تستخدم نظام التهوية الطبيعية أو المراوح, هل تحقق درجة البرودة والراحة المطلوبة في فصل الصيف؟
If natural and/or mechanical ventilation is used, does this achieve a satisfactory level of thermal comfort in summer?

- ○ نعم (Yes)
- ○ لا (No)

*25. كيف تقيس جودة النقاط التالية في منزلك؟
How do you rate the quality of the following:

| | رديء (Poor) | مقبول (Fair) | جيد (Good) | جيداً (Very good) | ممتاز (Excellent) |
|---|---|---|---|---|---|
| مستوى وجودة ودرجة الحرارة في المنزل بإستخدام أجهزة التكييف (The quality of thermal comfort from using air-conditioning in your dwelling) | ○ | ○ | ○ | ○ | ○ |
| جودة ودرجة الحرارة في المنزل بإستخدام التهوية الطبيعية في فصل الصيف (The quality of thermal comfort from using natural ventilation only in your dwelling in summer) | ○ | ○ | ○ | ○ | ○ |
| جودة الإضائة الطبيعية في منزلك (The quality of natural lighting in your dwelling) | ○ | ○ | ○ | ○ | ○ |
| جودة العزل الحراري في مبنى منزلك (The efficiency of insulation in the building envelope of your dwelling) | ○ | ○ | ○ | ○ | ○ |
| جودة العزل الحراري في زجاج الشبابيك الخارجية لمنزلك (The efficiency of external glazing in your dwelling) | ○ | ○ | ○ | ○ | ○ |
| جودة نظام جمع وإعادة إستخدام مياه الأمطار للري في منزلك (The efficiency of rainwater harvesting for your dwelling) | ○ | ○ | ○ | ○ | ○ |
| جودة نظام إعادة تدوير المياه المستخدمة في منزلك (The efficiency of grey water recycling system of your dwelling) | ○ | ○ | ○ | ○ | ○ |
| وجود وتوزيع المساحات المظلله في الساحة الخارجية لمنزلك (The efficiency of shading devices of your dwelling) | ○ | ○ | ○ | ○ | ○ |
| توفير المياه الساخنة في منزلك (The quality of Domistic Hot Water supply of your dwelling) | ○ | ○ | ○ | ○ | ○ |

*26. ضع وجهات نظرك حول المواضيع التالية المتعلقة بالعادات والتقاليد الإجتماعية الإسلامية في السعودية
Please indicate your point of view on the following socio-cultural issues:

| | لا أوافق بشدة (Strongly disagree) | لا أوافق (Disagree) | محايد (Neutral) | أوافق (Agree) | أوافق بشدة (Strongly agree) |
|---|---|---|---|---|---|
| هل توافق على أن تكون غرفة الضيافة واحدة ومختلطة بين الرجال والنساء في المنزل؟ (Would you agree to having only one guest room for both genders?) | ○ | ○ | ○ | ○ | ○ |
| هل توافق على أن تكون غرفة الطعام واحدة ومختلطة بين الرجال والنساء في المنزل؟ (Would you agree to having one dining/sitting room for both genders?) | ○ | ○ | ○ | ○ | ○ |
| هل توافق على تقليل مساحة غرف النوم على أن تتناسب مع عدد الأفراد في الغرفة؟ (Would you agree to having bedroom appropriately sized to fit the needs of occupant?) | ○ | ○ | ○ | ○ | ○ |
| هل توافق على أن تكون المنازل بأسطح مائلة بدلا من الأسطح المسطحة؟ (Would you agree to having a sloping roof instead of a flat roof?) | ○ | ○ | ○ | ○ | ○ |
| هل توافق على تقليل مساحة المنزل لهدف ترشيد الطاقة؟ (Would youagree to living in a smaller house in order to reduce energy demands?) | ○ | ○ | ○ | ○ | ○ |

*27. هل حجم ومساحة المنزل يعكس المكانة الإجتماعية؟ (Do you regard the size of someone's house as a symbol of the person's status or stature in society?.)

○ نعم (Yes)

○ لا (No)

○ ليست بالضرورة (Not necessary)

القسم الثالث/ أجب عن الأسئلة التالية المتعلقة بالمباني المستدامة المرشدة لل...

Section (3) Please answer the following questions about Sustainable Building

*28. هل سمعت سابقاً عن المباني المستدامة أو المباني الخضراء أو المباني المرشدة للطاقة الكهربائية؟
Have you ever heard of sustainable/low energy or green building?

- ○ نعم (Yes)
- ○ لا (No)

29. إذا كانت إجابتك بنعم, الرجاء التحديد؟
If 'Yes', please indicate where (you can select more than one answer).

- ☐ عن طريق الإنتر نت (Internet)
- ☐ الإعلام (Media)
- ☐ الأخبار (News)
- ☐ البرامج التلفزيونية (Television programmes)
- ☐ الخبرة الشخصية (Experience)
- ☐ الأصدقاء والمجتمع (Friends)
- ☐ الإعلانات (Advertisements)
- ☐ أخرى (Others)

أخرى- الرجاء التحديد (please specify)

*30. هل توافق على أن تكون المباني السكنية في المملكة العربية السعودية مستدامة ومرشدة للطاقة الكهربائية لحماية البيئة من إنبعاث غاز ثاني أكسيد الكربون؟
Do you agree that sustainable buildings must be adopted in Saudi Arabia in order to save energy and protect the environment from CO2 emissions?

- ○ نعم (Yes)
- ○ لا (No)

*31. ماهي وجهة نظرك بخصوص الإعتماد
على المباني المستدامة لتقليل إستهلاك الطاقة وانبعاث غاز ثاني اكسيد الكربون ؟ (What is your point of view about sustainability/reducing energy demand and reducing CO2 emission in domestic building for the good of the planet?)

- ☐ جيدة على النطاق الشخصي والعائلي (good of me/my family)
- ☐ جيدة ليتم تطبيقها على نطاق المملكة العربية السعودية (good of the nation Saudi Arabia)
- ☐ جيدة ليتم تطبيقها على مستوى العالم (Good for the world)
- ☐ محايد (Neutral)

∗32. لهدف ترشيد الطاقة في المباني السكنية, مامدى موافقتك بتركيب التقنيات الهندسية التالية التي تساعد في ترشيد إستهلاك الطاقة الكهربائية في منزلك الحالي؟

In terms of saving energy consumption in your dwelling, to what extent would you agree with the following statements regarding installations and techniques that contribute to energy savings?

| | لا أوافق بشدة (Strongly disagree) | لا أوافق (Disagree) | محايد (Neutral) | أوافق (Agree) | أوافق بشدة (Strongly agree) |
|---|---|---|---|---|---|
| مالك المنزل يجب أن يستخدم تقنية نظام الطاقة المتجددة لتحويل الطاقة الشمسية الى كهربائية بقدر الامكان لترشيد إستهلاك الطاقة المنتجة عن طريق شركة الكهرباء (The householder should install solar electricity generation system, i.e. photovoltaics, PV, in order to reduce consumption from the national electricity grid supply.) | ○ | ○ | ○ | ○ | ○ |
| مالك المنزل يجب ان يستخدم الطاقة الشمسية في تدفئة المياة المنزلية بدلاً من الكهرباء (Householders should use solar radiations for water heating instead of electricity to save energy) | ○ | ○ | ○ | ○ | ○ |
| مالك المنزل يجب أن يصمم نظام تظليل طبيعي حول الشبابيك الخاريجة لغرض منع وصول الحرارة الخارجية و ترشيد الطاقة الكهربائية (The householder should install a shading device around windows in order to save energy consumption.) | ○ | ○ | ○ | ○ | ○ |
| مالك المنزل يجب أن يستبدل الزجاج الرديء المنفرد الى زجاج فعال مزدوج مقاوم للحرارة لغرض ترشيد استهلاك الكهرباء في المنزل (The householder should replace the poor single glazing with an efficient double or triple glaze in order to save energy consumption.) | ○ | ○ | ○ | ○ | ○ |
| مالك المنزل يجب أن يضع نظام إعادة تدوير المياة المستخدمة لغرض الريء وزراعة حديقة خارجية حول المنزل (The householder should install a grey water recycling system for irrigation purposes, to create more vegetation around your dwelling.) | ○ | ○ | ○ | ○ | ○ |
| لايوجد توعية إجتماعية عند ملاك المنازل بخصوص المباني المستدامة المرشدة للطاقة (The householders have no awareness of low carbon energy buildings.) | ○ | ○ | ○ | ○ | ○ |
| هناك شح بخصوص منتجات المباني المستدامة في المملكة مثل تقنية نظام تحويل الطاقة الشمسية الى كهربائية (There are shortages of sustainable products such as PV on the Saudi market.) | ○ | ○ | ○ | ○ | ○ |
| الجهات الحكومية المعنية يجب أن تنظم سوق ومؤسسات لتعزز المباني المستدامة المرشدة للطاقة (The government should regulate the market and establishments to promote sustainable buildings.) | ○ | ○ | ○ | ○ | ○ |

**...القسم الرابع/ أجب عن الأسئلة التالية بخصوص المنازل المستقبلية في المملكة ال**

Section (4) Please answer the following questions about future dwellings in KSA

*33. **الرجاء ضع وجهات نظرك على النقاط التالية**

Please state your opinion on these points:

| | لا أوافق بشدة (Strongly disagree) | لا أوافق (Disagree) | محايد (Neutral) | أوافق (Agree) | أوافق بشدة (Strongly agree) |
|---|---|---|---|---|---|
| المنازل المستقبلية يجب أن تصمم هندسياً على أن تكون مرشدة للطاقة الكهربائية والتقليل من انبعاث ثاني اكسيد الكربون (Future dwellings in Saudi Arabia must be designed to save energy consumption and CO2 emissions .) | ○ | ○ | ○ | ○ | ○ |
| مساحات المنازل المستقبلية يجب أن تقلص وتتناسب مع عدد أفراد الأسرة لغرض ترشيد الطاقة (The sizes of future dwellings in Saudi Arabia should be reduced to fit the household members.) | ○ | ○ | ○ | ○ | ○ |
| المنازل المستقبلية يجب أن تصمم هندسيا تحت معايير الإستدامة لهدف ترشيد الطاقة الكهربائية وتكون إجبارية من الجهات الحكومية المعنية (Future dwellings must be designed according to sustainable criteria established as compulsory by the government.) | ○ | ○ | ○ | ○ | ○ |
| الجهات الحكومية المعنية مثل البلديات وشركات الكهرباء يجب أن تتخذ خطوة لتضع قوانين لإعتماد المباني السكنية المستدامة لحماية البيئة من المباني المهدره للطاقة (The government should take serious steps to introduce rules to adopt sustainable buildings in Saudi Arabia.) | ○ | ○ | ○ | ○ | ○ |

**شكراً لمشاركتكم**

Thank you in advance for your response.

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**الرجاء اضغط**

(Done)

# APPENDIX B- Experts consultations- Questionnaire samples (Round one)

## Introduction مقدمة

أتقدم لسعادتكم أنا نايف علي الدوسري (طالب دكتوراة تخصص التصميم الهندسي المعماري والبناء المستدام في كلية الهندسة – جامعة كاردف – بريطانيا ) بطلب مساهمتكم لبناء أفكار تصميمة للمباني السكنية المستدامة المرشدة للطاقة في المناخ الحار. هذة المرحلة من الدراسة تتضمن إستقصاء آراء الخبراء في المباني المستدامة المرشدة للطاقة الكهربائية في المملكة العربية السعودية حيث أن المنهجية الرئيسية في هذة الدراسة تكمن في إستشارة الخبراء في مجال الأستدامة في المباني والعمران

تتكون هذة الدراسة من ثلاثة مراحل
المرحلة الاولى: بناء الأفكار بالتعاون مع الخبراء
المرحلة الثانية: حصر الأفكار لتقليص المقترحات التصميمية
المرحلة الثالثة: تقييم الأفكار

يعد الغرض النهائي من هذه المرحلة بناء منهجية عمل إرشادي لتصميم مباني مستدامة مرشدة للطاقة الكهربائية في المناطق التي تتسم بمعدلات مرتفعة لدرجات الحرارة مثل المملكة العربية السعودية للوصول لمخرجات تساهم في تصميم مباني سكنية مستدامة ومرشدة للطاقة ومخفضة لإنبعاث ثاني أكسيد الكربون

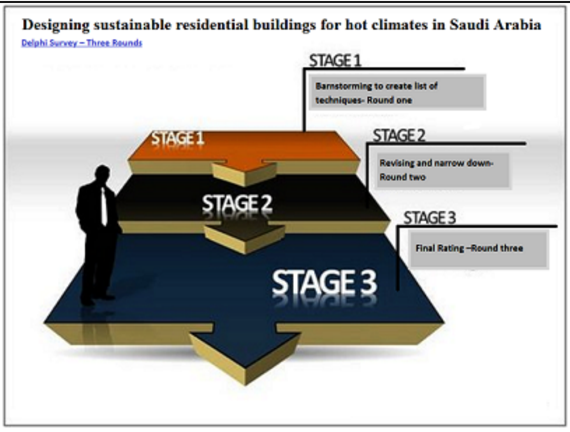
الإجابة على الإستبيان يستغرق تقريباً عشر دقائق ومشاركاتكم مهمة لبناء مستقبل مشرق ومفيدة لدعم هذه الدراسة بناءاً على خبراتكم العلمية والعملية والتي ستكون للغرض العلمي فقط كما سيتم التعامل مع الإجابات الشخصية بسرية تامة

I would like to introduce myself as Naief A. Aldossary; Ph.D candidate in the subject of Sustainable Architectural Design and Construction, Cardiff school of Engineering, Cardiff University -United Kingdom.

This research project utilizes "Delphi technique" as a research method and conducted as part of my broader investigation, focusing on designing sustainable residential buildings for hot climates in Saudi Arabia. The main purpose of this survey is identifying how to design a sustainable domestic building for hot climates, using Saudi Arabia as a case study. According to previous research conducted on this issue, findings demonstrate that the weaknesses of existing buildings are linked to the cooling systems (air conditioning), which consume the bulk of the energy consumption (in the form of kWh). This is quite high in comparison to other countries which also have similar hot climates.

In order to better understand how to design and sustain residential buildings in Saudi Arabia (low carbon energy building in a hot climate), your participation is sought. Your answers will be helpful in taking into consideration potential design factors in order to sustain domestic buildings in Saudi Arabia.

Responding to the questionnaire takes approximately 10 minutes and your individual privacy and the confidentiality of the information provided will be maintained in all published and written data analysis resulting from the study.




الرجاء أكتب بياناتك الشخصية *

Please type your demographic information

(Name) الإسم:

Company/ or organization جهة العمل:

Subject field مجال تخصصك:

Position المنصب:

Years of experience عدد سنوات الخبرة:

Email address البريد الإلكتروني:

Country الدولة:

## General View بشكل عام

* بشكل عام – في الدول ذات الطقس الحار مثل المملكة العربية السعودية هناك طرق وإجراءات مختلفة التي ترشد من إستهلاك الطاقة في المباني السكنية. الرجاء قم بتقييم الطرق المقترحة التالية لغرض ترشيد الطاقة في المباني حسب خبرتك

Generally, in hot climatic countries (e.g. Saudi Arabia) there are different methods and procedures that reduce energy demand in residential buildings. Based on your experience, please tick the most efficient energy reduction solutions from the choices below:

| | 1.Not Applicable غير قابلة للتطبيق | 2.Not Important ليست مهمة | 3.Somewhat Important مهمة إلى حد ما | 4.Moderate Important متوسطة الأهمية | 5.Very Important مهمًا |
|---|---|---|---|---|---|
| Building design (including architectural design, shape, size, shade, color and landscaping) التصميم المعماري الفعال للمبنى وتتضمن شكل وحجم المبنى, الألوان, توزيع الضل وتنسيق الحديقة الخارجية | ○ | ○ | ○ | ○ | ○ |
| Building Fabric (including used construction, insulation for external walls, roof, floor door and windows) فعالية عزل الحوائط والأرضيات والأسقف الخارجية | ○ | ○ | ○ | ○ | ○ |
| On-site renewable energy (solar energy, wind energy …etc) إستخدام الطاقة المتجددة مثل نظام الطاقة الشمسية | ○ | ○ | ○ | ○ | ○ |

If you choose "Not Applicable" for any criterion above, please justify briefly your opinion إذا أخترت غير قابلة للتطبيق الرجاء توضيح السبب من وجهة نظرك إن أمكن

## Section One: Architectural Design القسم الأول– التصميم المعماري

**في هذا الجزء سوف نتطرق لتقيم كفاءة البناء لغرض ترشيد الطاقة الكهربائية من خلال**

(1) **التصميم المعماري الفعال للمبنى**
Building Form
(2) **شكل المبنى**
Building Shape
(3) **تصميم الشبابيك الخارجية للمبنى**
Windows Design
(4) **توزيع الظل حول المبنى**
Shading devise
(5) **نظام التهوية والتكييف**
HVAC

* **التصميم المعماري للمبنى يلعب دور كبير في ترشيد الطاقة الكهربائية. الرجاء قيم التقنيات المختلفة التالية لغرض ترشيد الطاقة في المبنى**

Efficient Architectural design plays a significant role for energy saving. Please assess the techniques from the list below that can reduce the energy demand

| | 1.Not Applicable غير قابلة للتطبيق | 2.Not Important ليست مهمة | 3.Somewhat Important مهمة إلى حد ما | 4.Moderate Important متوسطة الأهمية | 5.Very Important مهمًا |
|---|---|---|---|---|---|
| Orientation of the building (south facing) إتجاه المبنى للناحية الجنوبية | ○ | ○ | ○ | ○ | ○ |
| Shading devices توزيع الضل حول المبنى | ○ | ○ | ○ | ○ | ○ |
| Minimizing building size as possible تقليل حجم المبنى بقدر الإمكان | ○ | ○ | ○ | ○ | ○ |
| Optimal design of building shape التصميم الفعال لشكل المبنى | ○ | ○ | ○ | ○ | ○ |
| Internal subdivisions of the building التقسيمات الداخلية للمبنى | ○ | ○ | ○ | ○ | ○ |

If you choose "Not Applicable" for any criterion above, please justify briefly your opinion
إذا أخترت غير قابلة للتطبيق الرجاء توضيح السبب من وجهة نظرك إن أمكن

**الرجاء أضف تقنيات أخرى لم تذكر في هذا السياق (المتعلقة بالتصميم المعماري للمبنى) بناءاً على خبرتك العملية**

Please add further techniques, in this regard, that not covered above based on your experience

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*شكل المبنى أحد معايير التصميم المعماري التي تتحكم في إستهلاك الطاقة: الرجاء قيم التقنيات المذكورة التالية من ناحية ترشيد إستهلاك الطاقة في المباني

Building shape: Please assess the techniques mentioned below as to their capacity to reduce energy demand in domestic buildings

| | 1.Not Applicable غير قابلة للتطبيق | 2.Not Important ليست مهمة | 3.Somewhat Important مهمة إلى حد ما | 4.Moderate Important متوسطة الأهمية | 5.Very Important مهمًا |
|---|---|---|---|---|---|
| Flat shape تصميم المبنى لتكون بالأسطح المسطحة | ○ | ○ | ○ | ○ | ○ |
| Slope shape to minimize exposure sun heat تصميم المبنى لتكون بالأسطح المائلة للتقليل من مواجهة حرارة الشمس | ○ | ○ | ○ | ○ | ○ |
| Using Green buildings techniques أستخدام تقنية الأسطح الخضراء | ○ | ○ | ○ | ○ | ○ |

If you choose "Not Applicable" for any criterion above, please justify briefly your opinion
إذا أخترت غير قابلة للتطبيق الرجاء توضيح السبب من وجهة نظرك إن أمكن

الرجاء أضف تقنيات أخرى لم تذكر في هذا السياق (المتعلقة بشكل المبنى) بناءاً على خبرتك العملية

Please add further techniques, in this regard, that not covered above based on your experience

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*تصميم الشبابيك الخارجية له دور في أستهلاك الطاقة: الرجاء قيم التقنيات التالية من ناحية ترشيد الطاقة الكهربائية في المباني

Please assess from the list below of windows' design techniques, the ones that can reduce energy demand in domestic buildings.

| | 1.Not Applicable غير قابلة للتطبيق | 2.Not Important ليست مهمة | 3.Somewhat Important مهمة إلى حد ما | 4.Moderate Important متوسطة الأهمية | 5.Very Important مهمًا |
|---|---|---|---|---|---|
| Reduce windows area تقليل مساحات الشبابيك الخارجية بقدر الإمكان | ○ | ○ | ○ | ○ | ○ |
| Reduce the number of windows تقليل عدد الشبابيك الخارجية بقدر الإمكان | ○ | ○ | ○ | ○ | ○ |
| Use canopies on top of windows to prevent the sun heat تركيب مظلات خارجية فوق الشبابيك لتمنع وصول حرارة الشمس | ○ | ○ | ○ | ○ | ○ |
| Grow grass in the front of each window زراعة أعشاب خضراء أمام كل شباك | ○ | ○ | ○ | ○ | ○ |

If you choose "Not Applicable" for any criterion above, please justify briefly your opinion
إذا أخترت غير قابلة للتطبيق الرجاء توضيح السبب من وجهة نظرك إن أمكن

الرجاء أضف تقنيات أخرى لم تذكر في هذا السياق (المتعلقة بتصميم الشبابيك الخارجية للمبنى) بناءاً على خبرتك العملية

Please add further techniques, in this regard, that not covered above based on your experience

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**توزيع الظل حول المبنى له دور في ترشيد الطاقة الكهربائية: الرجاء قيم التقنيات التالية المتعلقة بأساليب توزيع الظل لغرض ترشيد الطاقة الكهربائية في المباني** *

Shading device: Please assess the techniques below of shading design in terms of energy efficiency

| | 1.Not Applicable غير قابلة للتطبيق | 2.Not Important ليست مهمة | 3.Somewhat Important مهمة إلى حد ما | 4.Moderate Important متوسطة الأهمية | 5.Very Important مهمًا |
|---|---|---|---|---|---|
| Use high shading devices around the building on top of external walls أستخدام مظلات عالية فوق الجدران الخاريجة لتوفير ظل حول المبنى وتقليل درجة الحرارة الخارجية | ○ | ○ | ○ | ○ | ○ |
| Use internal and/or external shutter for windows to prevent unwanted solar gains أستخدام ستائر داخلية وخارجية للشبابيك لتقليل حرارة الشمس | ○ | ○ | ○ | ○ | ○ |
| Use efficient court yard landscaping design to provide shade around the building تصميم حديقة في الفناء الخارجي لتوزيع الظل حول المبنى | ○ | ○ | ○ | ○ | ○ |
| Use horizontal canopy to create shade أستخدام مظلات أفقية لتوفير ظل عندما تكون الشمس عمودية | ○ | ○ | ○ | ○ | ○ |

If you choose "Not Applicable" for any criterion above, please justify briefly your opinion إذا أخترت غير قابلة للتطبيق الرجاء توضيح السبب من وجهة نظرك إن أمكن

**الرجاء أضف تقنيات أخرى لم تذكر في هذا السياق (المتعلقة بتوزيع الظل حول المبنى) بناءاً على خبرتك العملية**

Please add further techniques, in this regard, that not covered above based on your experience

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نظام التكييف والتهوية له دور كبير في إستهلاك الطاقة: الرجاء قيم التقنيات التالية المتعلقة بأساليب التكييف أو التدفئة لغرض تقليل إستهلاك الطاقة الكهربائية في المباني *

HVAC: Please assess the list of techniques below related to cooling and/ or heating from an energy saving perspective

| | 1.Not Applicable غير قابلة للتطبيق | 2.Not Important ليست مهمة | 3.Somewhat Important مهمة إلى حد ما | 4.Moderate Important متوسطة الأهمية | 5.Very Important مهمًا |
|---|---|---|---|---|---|
| Divide the internal rooms in the building into zones to create separate cooling and/ or heating units and use rooms when the need arises only تقسيم المبنى من الداخل إلى مناطق أو وحدات لتكون كل وحدة نظام تكييف مستقل | ○ | ○ | ○ | ○ | ○ |
| Use sensors for air conditioning that control temperature of the rooms أستخدام حساسات للتحكم في درجة حرارة الغرف | ○ | ○ | ○ | ○ | ○ |
| Use mechanical ventilation techniques أستخدام تقنيات التهوية الميكانيكية | ○ | ○ | ○ | ○ | ○ |
| Use ground heat exchange techniques أستخدام تقنيات التبريد من خلال مرور الهواء داخل الأرض | ○ | ○ | ○ | ○ | ○ |

If you choose "Not Applicable" for any criterion above, please justify briefly your opinion إذا أخترت غير قابلة للتطبيق الرجاء توضيح السبب من وجهة نظرك إن أمكن

الرجاء أضف تقنيات أخرى لم تذكر في هذا السياق (المتعلقة بنظام التكييف في المبنى) بناءاً على خبرتك العملية

Please add further techniques, in this regard, that not covered above based on your experience

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**التهوية الطبيعية تساهم في ترشيد الطاقة للمباني: الرجاء قيم الخيارات التالية للتهوية الطبيعية التي تساهم في ترشيد الطاقة الكهربائية للمباني** *

Natural ventilation: Please assess the list of ventilation techniques below from an energy reduction perspective

| | 1.Not Applicable غير قابلة للتطبيق | 2.Not Important ليست مهمة | 3.Somewhat Important مهمة إلى حد ما | 4.Moderate Important متوسطة الأهمية | 5.Very Important مهماً |
|---|---|---|---|---|---|
| Use windows only to ventilate the building أستخدام الشبابيك فقط لتهوية المبنى | ○ | ○ | ○ | ○ | ○ |
| Use ventilation tower technique to create air shafts/stacks أستخدام تقنية التهوية الطبيعية عن طريق أبراج التهوية والمداخن في المبنى | ○ | ○ | ○ | ○ | ○ |
| Design the indoor of the building by open plan in order to provide interior airflow تصميم المبنى من الداخل لتكون مفتوحة وتسهل تدفق التيار الهوائي | ○ | ○ | ○ | ○ | ○ |
| Each room should be designed to have two opening windows to promote air flow كل غرفة يجب أن تحتوي على شباكين مفتوحة لتوفر تيار هوائي | ○ | ○ | ○ | ○ | ○ |

If you choose "Not Applicable" for any criterion above, please justify briefly your opinion إذا أخترت غير قابلة للتطبيق الرجاء توضيح السبب من وجهة نظرك إن أمكن

**الرجاء أضف تقنيات أخرى لم تذكر في هذا السياق (المتعلقة بنظام التهوية الطبيعية) بناءاً على خبرتك العملية**

Please add further techniques, in this regard, that not covered above based on your experience

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## Section Two: Building Fabric الغلاف الخارجة للمبنى – مواد البناء المستخدمة

**المواد المستخدمة للغلاف الخارجي للمبنى أحد العوامل المهمة التي تساهم في ترشيد استهلاك الطاقة الكهربائية في المباني. بناءاً على خبرتك,الرجاء أجب عن الاسئلة التالية**

Section (2)- Building' envelope (Fabric): this is one of the most significant factors that contribute to energy savings. Based on your experience please answer the questions below:

**في هذا الجزء سوف نتطرق لتقيم كفاءة البناء لترشيد الطاقةالكهربائية في المبنى من خلال**

(1) **المواد المستخدمة في البناء**
Building Fabric
(2) **تصميم الجدران الخارجية**
External Wall
(3) **تصميم زجاج الشبابيك الخارجية**
Windows
(4) **تصميم السطح الخارجي للمبنى**
Building Roof
(5) **تصميم أرضيات المبنى**
Building Floor

**بشكل عام: قيم الطرق الفعالة التالية التي لها تأثير في ترشيد الطاقة الكهربائية في المباني عن طريق المواد المستخدمة للبناء للغلاف الخارجي** *

Generally, please assess building envelope efficient factors that reduce energy demand

| | 1.Not Applicable غير قابلة للتطبيق | 2.Not Important ليست مهمة | 3.Somewhat Important مهمة إلى حد ما | 4.Moderate Important متوسطة الأهمية | 5.Very Important مهمًا |
|---|---|---|---|---|---|
| Thicknesses سمك الجدران الخارجية والأسقف والأرضيات | ○ | ○ | ○ | ○ | ○ |
| Conductivity of materials مدى قلة توصيل الحرارة في المواد المستخدمة لبناء الغلاف الخارجي للمبنى | ○ | ○ | ○ | ○ | ○ |
| Resistance of the materials مدى مقاومة الحرارة للمواد المستخدمة في بناء الغلاف الخارجي للمبنى | ○ | ○ | ○ | ○ | ○ |
| Type of Insulation materials نوع ومدى فعالية العوازل الحرارية المستخدمة | ○ | ○ | ○ | ○ | ○ |

If you choose "Not Applicable" for any criterion above, please justify briefly your opinion
إذا أخترت غير قابلة للتطبيق الرجاء توضيح السبب من وجهة نظرك إن أمكن

*** الجدران الخاريجة: وتحتوي على أنواع مختلفه من مواد البناء المستخدمة. الرجاء قيم مواد البناء التالية التي تستخدم في الجدران الخارجية لغرض ترشيد الطاقة الكهربائية في المباني**

External walls: This involves multiple types of construction materials used for external walls. Please assess the techniques below from an energy reduction perspective.

| | 1.Not Applicable غير قابلة للتطبيق | 2.Not Important ليست مهمة | 3.Somewhat Important مهمة إلى حد ما | 4.Moderate Important متوسطة الأهمية | 5.Very Important مهمًا |
|---|---|---|---|---|---|
| Design external walls with Mud in order to be highly insulated إستخدام مادة الطين في الجدران الخارجية لغرض رفع فاعلية العزل الحراري | ○ | ○ | ○ | ○ | ○ |
| Design external walls with solid Red- clay brick إستخدام الطوب الأحمر الصلب الغير مفرغ أو الطوب الفخاري في الجدران الخارجية لغرض رفع فاعلية العزل الحراري | ○ | ○ | ○ | ○ | ○ |
| Use Wood materials for external walls to increase their insulation إستخدام الخشب كأحد عناصر بناء الجدران الخارجية لغرض رفع فاعلية العوازل الحرارية | ○ | ○ | ○ | ○ | ○ |
| Use Stone built external walls تصميم الجدران الخارجية لتكون مبنية بالحجر الصلب لغرض رفع كفائة فاعلية العزل الحراري | ○ | ○ | ○ | ○ | ○ |
| Use cavity techniques in external walls أستخدام تقنية الفراغات الداخلية مع الطين او الطوب العازل لغرض رفع كفائة فاعلية العزل الحراري للجدران الخارجية | ○ | ○ | ○ | ○ | ○ |

If you choose "Not Applicable" for any criterion above, please justify briefly your opinion إذا أخترت غير قابلة للتطبيق الرجاء توضيح السبب من وجهة نظرك إن أمكن

**الرجاء أضف تقنيات أخرى لم تذكر في هذا السياق (المتعلقة بتصميم وإختيار مواد البناء للجدران الخارجية) بناءاً على خبرتك العملية**

Please add further techniques, in this regard, that not covered above based on your experience

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* الشبابيك الخارجية تحتوي على أنواع مختلفة من تقنيات وتصاميم الزجاج. قيم التقنيات التالية لغرض ترشيد إستهلاك الطاقة الكهربائية في المباني

External windows: This contains multiple types of glazing design techniques. Please assess the techniques below that reduce energy demand

| | 1.Not Applicable غير قابلة للتطبيق | 2.Not Important ليست مهمة | 3.Somewhat Important مهمة إلى حد ما | 4.Moderate Important متوسطة الأهمية | 5.Very Important مهمًا |
|---|---|---|---|---|---|
| Increase the thickness of glazing زيادة سماكة الزجاج في الشبابيك | ○ | ○ | ○ | ○ | ○ |
| Use double or triple glazing with air between glazing panels إستخدام زجاج طبقتين أو ثلاث طبقات مع غاز الهواء بينها لغرض رفع كفائة العزل الحراري | ○ | ○ | ○ | ○ | ○ |
| Use double or triple glaze with argon gas between glazing panels إستخدام طبقتين أو ثلاث طبقات من الزجاج مع غاز الأرجون بينها لغرض رفع كفائة العزل الحراري | ○ | ○ | ○ | ○ | ○ |
| Use highly air tight windows تصميم الشبابيك الخارجية مع إحكام تسرب الهواء | ○ | ○ | ○ | ○ | ○ |

If you choose "Not Applicable" for any criterion above, please justify briefly your opinion إذا أخترت غير قابلة للتطبيق الرجاء توضيح السبب من وجهة نظرك إن أمكن

الرجاء أضف تقنيات أخرى لم تذكر في هذا السياق (تصميم زجاج الشبابيك الخارجية) بناءاً على خبرتك العملية

Please add further techniques, in this regard, that not covered above based on your experience

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*** قيم أسقف (الأسطح) المباني المتضمنة مواد البناء المستخدمة له دور في ترشيد إستهلاك الطاقة الكهربائية في المباني. التقنيات التالية لغرض ترشيد إستهلاك الطاقة الكهربائية**

Efficient Roof: This includes the roof construction materials. Please assess the list of techniques below that reduce energy consumption.

| | 1.Not Applicable غير قابلة للتطبيق | 2.Not Important ليست مهمة | 3.Somewhat Important مهمة إلى حد ما | 4.Moderate Important متوسطة الأهمية | 5.Very Important مهمًا |
|---|---|---|---|---|---|
| Design the external roof above the structure concrete with rain insulation and wood materialsتصميم الأسقف الخارجية للمباني لتكون مواد عازلة للمطر ومادة الخشب فوق الخرسانة المسلحة | ○ | ○ | ○ | ○ | ○ |
| Design the external roofs above the structure concrete by efficient insulation materials and concrete tilesتصميم الأسقف الخارجية بمواد عازلة حرارية فوق الخرسانة المسلحة وبلاط | ○ | ○ | ○ | ○ | ○ |
| Design the external roofs above the structure concrete by green grass to increase the insulationتصميم الأسقف الخارجية بعد الخرسانة المسلحة بزراعة الأعشاب الخضراء لتزيد من كفائة العزل الحراري | ○ | ○ | ○ | ○ | ○ |
| Create a cavity above the structure, ventilated at night to prevent sun direct heat تصميم الأسقف الخارجية بعمل فجوة بين الخرسانة المسلحة وأرضية السطح لمرور تيار هوائي لغرض إمتصاص حرارة أشعة الشمس | ○ | ○ | ○ | ○ | ○ |

If you choose "Not Applicable" for any criterion above, please justify briefly your opinion
إذا أخترت غير قابلة للتطبيق الرجاء توضيح السبب من وجهة نظرك إن أمكن

**الرجاء أضف تقنيات أخرى لم تذكر في هذا السياق (المتعلقة بتصميم وإختيار مواد البناء للسطح الخارجي للمبنى) بناءاً على خبرتك العملية**

Please add further techniques, in this regard, that not covered above based on your experience

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* التصميم المقاوم الفعال لأرضية المبنى له دور في ترشيد إستهلاك الطاقة والتي تتضمن المواد المستخدمة في البناء بعد الخرسانات والقواعد الإنشائية. قيم التقنيات التالية المتعلقة في تصميم طبقات أرضية المباني لغرض ترشيد الطاقة الكهربائية

Efficient Floor (in addition to the basement structure): this includes the used construction materials on the floor. Please assess the techniques below from an energy reduction perspective

| | 1.Not Applicable غير قابلة للتطبيق | 2.Not Important ليست مهمة | 3.Somewhat Important مهمة إلى حد ما | 4.Moderate Important متوسطة الأهمية | 5.Very Important مهمًا |
|---|---|---|---|---|---|
| Use mud insulation, mortar and concrete tiles أستخدام مواد الطين العازل والبلاط في الأرضيات | ○ | ○ | ○ | ○ | ○ |
| Use wood insulation materials أستخدام الخشب كنوع من العوازل في الأرضيات | ○ | ○ | ○ | ○ | ○ |
| Use thick layer of sand and concrete tiles أستخدام طبقة سميكة من الرمل والبلاط | ○ | ○ | ○ | ○ | ○ |
| Use layer of concrete including sand and concrete tiles أستخدام طبقة إضافية من الخرسانة المسلحة المخلوطة مع الرمل ثم البلاط كنوع من العوازل | ○ | ○ | ○ | ○ | ○ |

If you choose "Not Applicable" for any criterion above, please justify briefly your opinion
إذا أخترت غير قابلة للتطبيق الرجاء توضيح السبب من وجهة نظرك إن أمكن

الرجاء أضف تقنيات أخرى لم تذكر في هذا السياق (المتعلقة بتصميم وإختيار مواد البناء في الأرضيات للمبنى) بناءاً على خبرتك العملية

Please add further techniques, in this regard, that not covered above based on your experience

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## Section Three: On-site renewable energy تقنية الطاقة المتجددة في المباني

**الطاقة المتجددة في المباني لها دور فعال في أستخدام الطاقة الطبيعية وتحويلها إلى كهربائية والتي يجب أن تطبق في المباني السكنية**

**توليد الطاقة الكهربائية عن طريق أستخدام شرائح الطاقة الشمسية: هناك طرق مختلفة لتحويل الطاقة الشمسية إلى طاقة كهربائية. قيم الطرق والتقنيات التالية بناءاً على خبرتك** *

Energy generation using (Photovoltaic PV): There are multiple ways of using PV in buildings. Based on your experience please assess the efficient ways that can generate more electricity

| | 1.Not Applicable غير قابلة للتطبيق | 2.Not Important ليست مهمة | 3.Somewhat Important مهمة إلى حد ما | 4.Moderate Important متوسطة الأهمية | 5.Very Important مهمًا |
|---|---|---|---|---|---|
| Use the PV on top of the building oriented south facing تركيب الشرائح الشمسية في أعلى المبنى وتوجيهها إلى أتجاه الجنوب | ○ | ○ | ○ | ○ | ○ |
| Use the PV on top of the building oriented east and west facingتركيب الشرائح الشمسية في أعلى المبنى وتوجيهها بأتجاهي الشرق والغرب | ○ | ○ | ○ | ○ | ○ |
| PV on external windows تركيب الشرائح الشمسية على الشبابيك الخارجية | ○ | ○ | ○ | ○ | ○ |
| Use solar wall techniques أستخدام تقنية توليد الطاقة الشمسية عن طريق الجدران الخارجية | ○ | ○ | ○ | ○ | ○ |

If you choose "Not Applicable" for any criterion above, please justify briefly your opinion
إذا أخترت غير قابلة للتطبيق الرجاء توضيح السبب من وجهة نظرك إن أمكن

**الرجاء أضف تقنيات أخرى لم تذكر في هذا السياق (المتعلقة بالطاقة المتجددة في المبنى) بناءاً على خبرتك العملية**

Please add further techniques, in this regard, that not covered above based on your experience

1

2

3

4

## Section Four: Social- cultural image العادات والتقاليد والصورة الإجتماعية

العادات والتقاليد و الصورة الإجتماعية :تقاليد السكان في المملكة العربية السعودية يعكس إستهلاك الطاقة في المباني السكنية. من فضلك قيم التقنيات التالية لغرض ترشد إستهلاك الطاقة المتعلقة بإستخدامات الغرف الناتجة من العادات والتقاليد

الرجاء قم بتقييم التقنيات التالية المتعلقة بالإستخدامات الأجتماعية للغرف لغرض ترشيد الطاقة في المباني السكنية*

Social/cultural image: Please assess the techniques below in terms of energy saving related to room usage

| | 1.Not Applicable غير قابلة للتطبيق | 2.Not Important ليست مهمة | 3.Somewhat Important مهمة إلى حد ما | 4.Moderate Important متوسطة الأهمية | 5.Very Important مهمًا |
|---|---|---|---|---|---|
| Reduce area of rooms that have highest use period (e.g. bed rooms) تقليل مساحات الغرف الأكثر إستخدام مثل غرف النوم | ○ | ○ | ○ | ○ | ○ |
| o Use the second floor of the building for rooms that have less usage period (e.g guest rooms) and use the ground floor for rooms that have high usage period(e.g. bed room of sitting area) تصميم المبنى ليكون إستخدام الطابق الثاني للغرف الأقل إستخدام مثل صلات الضيوف وإستخدام الغرف في الطابق الأرضي للغرف الأكثر إستخدام لترشيد إستهلاك الطاقة | ○ | ○ | ○ | ○ | ○ |
| As the underground is cooler, use the underground level instead of the over ground levels أستخدام أدوار تحت الأرض بدلاً من الادوار فوق الأرض | ○ | ○ | ○ | ○ | ○ |

If you choose "Not Applicable" for any criterion above, please justify briefly your opinion إذا أخترت غير قابلة للتطبيق الرجاء توضيح السبب من وجهة نظرك إن أمكن

الرجاء أضف تقنيات أخرى لم تذكر في هذا السياق (المتعلقة بالعادات والتقاليد) بناءاً على خبرتك العملية

Please add further techniques, in this regard, that not covered above based on your experience

1

2

3

4

**تعليقات عامة إن وجد**
General Comments

هنا نهاية الإستفتاء. شكراً لمشاركتكم. الرجاء اضغط
(Done)
نايف بن علي الدوسري
طالب دكتوراة في الهندسة المعمارية والبناء
الإستدامة في المباني وترشيد الطاقة
جامعة كاردف
بريطانيا

This is the end of the questionnaire. Thank you for your participation. Pleas click (Done)

Naief A. Aldossary
Ph.D Candidate in Architectural Engineering and Construction
Cardiff School of Engineering
Cardiff University
Cardiff- Wales
United Kingdom

# APPENDIX C- Experts consultations- Questionnaire samples (Round two)

introduction مقدمة

سعادة الخبير
[illegible] التوفيق. هذا الأستبانة هي للمرحلة الثانية والأخيرة
بخصوص وضع أستراتيجيات لتصميم مباني سكنية مستدامة مرشدة للطاقة الكهربائية في المناخ الحار مثل المملكة العربية السعودية. كما
[illegible]
المرحلة الثانية (المرحلة الحالية) هي التقييم النهائي للمعايير المتضمنة والمدعمة بمعايير جديدة تم إضافتها بتوصية من الخبراء في المرحلة السابقة من الأستطلاع

أنت أحد الخبراء المشاركين في الدراسة والمساهمين في المرحلة الأولى وأرجو مساهمتك في هذا الأستبيان للمرحلة الثانية بتقييم المعايير
[illegible]

هذا الأستبيان لايتطلب أضافة معايير جديدة وأنما فقط معايير ليتم تقييمها من سعادتكم وهذا الأستبيان لن يستغرق أكثر من 10 دقائق من وقتكم الثمين

سائلين المولى التوفيق

Dear Expert,
Firstly I would like to thank you for your participation in the past round and for your useful feedback and comments in support of the study. As mentioned initially, three rounds are needed to reach expert consensus on each criterion.

In order to better understand how to design and sustain residential buildings in Saudi Arabia (that is, how to achieve low carbon energy building in a hot climate), your participation is sought. Your answers will be helpful in evaluating potential design factors for sustaining domestic buildings in Saudi Arabia. It will take approximately 10 minutes to respond to the questionnaire and your individual privacy, as well as the confidentiality of the information provided, will be maintained in all published and written data analysis resulting from the study.

***1. الرجاء أكتب بياناتك الشخصية**
**Please type your demographic information**

Name الإسم:
Organization جهة العمل:
Email address البريد الألكتروني:

## Section One: Architectural Design القسم الأول- التصميم المعماري

في هذا الجزء هناك معايير جديدة تساهم في تصميم مباني سكنية مستدامة مرشدة للطاقة الكهربائية. هذة المعايير متعلقة في التصميم
[illegible] .
الرجاء ساهم في تقييم المعايير أدناه حسب خبرتك العلمية والعملية

In this part of questionnaire, there are many other different design strategies and criteria have been added based on experts' feedback. Pleas assess each criteria individually based on your experience

***2. التصميم المعماري للمبنى يلعب دور كبير في ترشيد الطاقة الكهربائية. الرجاء قيم التقنيات المختلفة التالية لغرض ترشيد الطاقة في المبنى**

**Efficient Architectural design plays a significant role for energy saving. Please assess the techniques from the list below that can reduce the energy demand**

| | ليست مهمة Not Important | قليلة الأهمية Less Important | مهمة Important | مهمًا Very important | فائقة الأهمية Extremely important |
|---|---|---|---|---|---|
| Orientation of the building (south facing) إتجاه المبنى للناحية الجنوبية | | | | | |
| Shading devices توزيع الضل حول المبنى | | | | | |
| Minimizing building size as possible تقليل حجم المبنى بقدر الإمكان | | | | | |
| Optimal design of building shape التصميم الفعال لشكل المبنى | | | | | |
| Internal subdivisions of the building التقسيمات الداخلية للمبنى | | | | | |

***3. شكل المبنى أحد معايير التصميم المعماري التي تتحكم في إستهلاك الطاقة: الرجاء قيم التقنيات المذكورة التالية من ناحية ترشيد إستهلاك الطاقة في المباني**

**Building shape: Please assess the techniques mentioned below as to their capacity to reduce energy demand in domestic buildings**

| | ليست مهمة Not Important | قليلة الأهمية Less Important | مهمة Important | مهمًا Very important | فائقة الأهمية Extremely important |
|---|---|---|---|---|---|
| Flat shape تصميم المبنى لتكون بالأسطح المسطحة | | | | | |
| Slope shape to minimize exposure sun heat تصميم المبنى لتكون بالأسطح المائلة للتقليل من مواجهة حرارة الشمس | | | | | |
| Using Green buildings techniques أستخدام تقنية الأسطح الخضراء | | | | | |

***4. تصميم الشبابيك الخارجية له دور في أستهلاك الطاقة: الرجاء قيم التقنيات التالية من ناحية ترشيد الطاقة الكهربائية في المباني**

**Please assess from the list below of windows' design techniques, the ones that can reduce energy demand in domestic buildings.**

| | ليست مهمة Not Important | قليلة الأهمية Less Important | مهمة Important | مهمًا Very important | فائقة الأهمية Extremely important |
|---|---|---|---|---|---|
| Reduce windows area تقليل مساحات الشبابيك الخارجية بقدر الإمكان | | | | | |
| Reduce the number of windows تقليل عدد الشبابيك الخارجية بقدر الإمكان | | | | | |
| Use canopies on top of windows to prevent the sun heatتركيب مظلات خارجية فوق الشبابيك لتمنع وصول حرارة الشمس | | | | | |
| Grow grass in the front of each window زراعة أعشاب خضراء أمام كل شباك | | | | | |

**5. توزيع الظل حول المبنى له دور في ترشيد الطاقة الكهربائية: الرجاء قيم التقنيات التالية المتعلقة بأساليب توزيع الظل لغرض ترشيد الطاقة الكهربائية في المباني**

**Shading device: Please assess the techniques below of shading design in terms of energy efficiency**

| | ليست مهمة Not Important | قليلة الأهمية Less Important | مهمة Important | مهمًا Very important | فائقة الأهمية Extremely important |
|---|---|---|---|---|---|
| Use high shading devices around the building on top of external walls أستخدام مظلات عالية فوق الجدران الخاريجة لتوفير ظل حول المبنى وتقليل درجة الحرارة الخارجية | ○ | ○ | ○ | ○ | ○ |
| Use internal and/or external shutter for windows to prevent unwanted solar gains أستخدام ستائر داخلية وخارجية للشبابيك لتقليل حرارة الشمس | ○ | ○ | ○ | ○ | ○ |
| Use efficient court yard landscaping design to provide shade around the building تصميم حديقة في الفناء الخارجي لتوزيع الظل حول المبنى | ○ | ○ | ○ | ○ | ○ |
| Use horizontal canopy to create shade أستخدام مظلات أفقية لتوفير ظل عندما تكون الشمس عمودية | ○ | ○ | ○ | ○ | ○ |

**6. نظام التكييف والتهوية له دور كبير في إستهلاك الطاقة: الرجاء قيم التقنيات التالية المتعلقة بأساليب التكييف أو التدفئة لغرض تقليل إستهلاك الطاقة الكهربائية في المباني**

**HVAC: Please assess the list of techniques below related to cooling and/ or heating from an energy saving perspective**

| | ليست مهمة Not important | قليلة الأهمية Less important | مهمة Important | مهمًا Very important | فائقة الأهمية Extremely important |
|---|---|---|---|---|---|
| Divide the internal rooms in the building into zones to create separate cooling and/ or heating units and use rooms when the need arises only تقسيم المبنى من الداخل إلى مناطق أو وحدات لتكون كل وحدة نظام تكييف مستقل | ○ | ○ | ○ | ○ | ○ |
| Use sensors for air conditioning that control temperature of the rooms أستخدام حساسات للتحكم في درجة حرارة الغرف | ○ | ○ | ○ | ○ | ○ |
| Use mechanical ventilation techniques أستخدام تقنيات التهوية الميكانيكية | ○ | ○ | ○ | ○ | ○ |
| Use ground heat exchange techniques أستخدام تقنيات التبريد من خلال مرور الهواء داخل الأرض | ○ | ○ | ○ | ○ | ○ |

***7. التهوية الطبيعية تساهم في ترشيد الطاقة للمباني: الرجاء قيم الخيارات التالية للتهوية الطبيعية التي تساهم في ترشيد الطاقة الكهربائية للمباني**

**Natural ventilation: Please assess the list of ventilation techniques below from an energy reduction perspective**

| | ليست مهمة Not important | قليلة الأهمية Less important | مهمة Important | مهمًا Very important | فائقة الأهمية Extremely important |
|---|---|---|---|---|---|
| Use windows only to ventilate the building أستخدام الشبابيك فقط لتهوية المبنى | ○ | ○ | ○ | ○ | ○ |
| Use ventilation tower technique to create air shafts/stacks أستخدام تقنية التهوية الطبيعية عن طريق أبراج التهوية والمداخن في المبنى | ○ | ○ | ○ | ○ | ○ |
| Design the indoor of the building by open plan in order to provide interior airflow تصميم المبنى من الداخل لتكون مفتوحة وتسهل تدفق التيار الهوائي | ○ | ○ | ○ | ○ | ○ |
| Each room should be designed to have two opening windows to promote air flow كل غرفة يجب أن تحتوي على شباكين مفتوحة لتوفر تيار هوائي | ○ | ○ | ○ | ○ | ○ |

***8. المعايير التالية أدناه هي معايير جديدة مضافة بناءاً على توصية الخبراء في المرحلة السابقة من الدراسة. الرجاء قيم المعايير ادناه بناء على خبرتك العلمية والعملية**

**Below are the many new criteria which have been added, based on experts' participation. Please assess these criteria on the basis of your own experience.**

| | ليست مهمة Not important | قليلة الأهمية Less important | مهمة Important | مهمًا Very important | فائقة الأهمية Extremely important |
|---|---|---|---|---|---|
| Place windows in the wall in order to have natural light and air stock وضع الشبابيك في أماكن التي تسهل أكثر مرور للأضائة الطبيعية والتيار الهوائي | ○ | ○ | ○ | ○ | ○ |
| Use colour glaze for external windows أستخدام زجاج ملون للشبابيك الخارجية في المبنى | ○ | ○ | ○ | ○ | ○ |
| Design the building so as to have space inside which will support the natural ventilation تصميم المبنى ليحتوي على فراغات داخلية مفتوحة لتدعم التهوية الطبيعية | ○ | ○ | ○ | ○ | ○ |
| Place the windows in the north side, with solar collection in the south face تخصيص الشبابيك في الواجهه الشمالية بينما الشرائح الشمسية في الواجهه الجنوبية | ○ | ○ | ○ | ○ | ○ |
| Orient the building to the north to provide ventilation and avoid solar heat توجية المبنى للأتجاه الشمالي لتسهل عملية التهوية الطبيعية ولتجنب الأشعاع الشمسي | ○ | ○ | ○ | ○ | ○ |
| Place natural skylight windows in the roof وضع شبابيك على سقف المبنى لتوفير أضائة طبيعية | ○ | ○ | ○ | ○ | ○ |
| Use an efficient design to obtain natural ventilation أستخدام التقنيات الفعالة للتهوية الطبيعية | ○ | ○ | ○ | ○ | ○ |
| Use attached house techniques أستخدام تقنية المباني المتلاصقة | ○ | ○ | ○ | ○ | ○ |
| Reduce the size and number of southern windows تقليل مساحة وعدد الشبابيك في الناحية الجنوبية | ○ | ○ | ○ | ○ | ○ |
| Use the technique of designing the building according to a depth plan, with a rectangular shape تصميم المبنى لتكون على شكل مستطيل طولي | ○ | ○ | ○ | ○ | ○ |
| Reduce the number of windows on the east and west sides تقليل عدد الشبابيك في الأتجاهين الشرقي والغربي | ○ | ○ | ○ | ○ | ○ |
| Use light colours for external walls أستخدام الوان فاتحة للجدران الخارجية | ○ | ○ | ○ | ○ | ○ |
| Increase green areas around the building زيادة مساحة المسطحات الخضراء حول المبنى | ○ | ○ | ○ | ○ | ○ |
| Use efficient finishing materials with high R-Value أستخدام مواد ذو مقاومة عالية للحرارة في التشطيبات الخارجية للمبنى | ○ | ○ | ○ | ○ | ○ |
| Design the building to take wind direction into account تصميم المبنى مع الأخذ في الأعتبار أتجاه الرياح لدعم التهوية الطبيعية | ○ | ○ | ○ | ○ | ○ |
| Consider fitting the building within its surrounding context تصميم المبنى ليكون ملائم مع البيئة المحيطة | ○ | ○ | ○ | ○ | ○ |
| Use sun louver techniques أستخدام تقنية تضليل الشبابيك الخارجية عن طريق فتحات صغيرة ورواشين | ○ | ○ | ○ | ○ | ○ |
| Shading in Ventilated Facades إستخدام تقنية الضل والتهوية على كامل واجهة المبنى | ○ | ○ | ○ | ○ | ○ |
| Use planting shades instead of steel shades in windows أستخدام الزراعة لتوفير الضل بدل من الحديد | ○ | ○ | ○ | ○ | ○ |

| | | | | | |
|---|---|---|---|---|---|
| Use sun reflection design techniques أستخدام تقنيات أنعكاس ضوء الشمس في التصميم | ○ | ○ | ○ | ○ | ○ |
| Reduce the width of the south facing as much as possible تقليل عرض الواجة الجنوبية بقدر المستطاع | ○ | ○ | ○ | ○ | ○ |
| Employ Building Management Systems (BMS) to control the lighting for the whole building أستخدام تقنيات نظام إدارة المبنى للتحكم في الأضائة | ○ | ○ | ○ | ○ | ○ |
| Use roof shading techniques أستخدام تقنيات الضل في الأسطح | ○ | ○ | ○ | ○ | ○ |

## Section Two: Building Fabric الغلاف الخارجة للمبنى - مواد البناء المستخدمة

في هذا الجزء هناك معايير تصميمية تساهم في ترشيد الطاقة في المباني والمتخصصة في التصميم الفعال للغلاف الخارجي للمبنى . بعضها تم إدراجها [illegible] في المرحلة السابقة. الرجاء ساهم في تقييم المعايير أدناه حسب خبرتك العلمية والعملية

In this part of questionnaire, there are many other different design strategies and criteria have been added based on experts' feedback. Pleas assess each criteria individually based on your experience

***9. بشكل عام: قيم الطرق الفعالة التالية التي لها تأثير في ترشيد الطاقة الكهربائية في المباني عن طريق المواد المستخدمة للبناء للغلاف الخارجي**

**Generally, please assess building envelope efficient factors that reduce energy demand**

| | ليست مهمة Not important | قليلة الأهمية Less important | مهمة Important | مهمًا Very important | فائقة الأهمية Extremely important |
|---|---|---|---|---|---|
| Thicknesses of house Envelop سماكة الجدران الخارجية والأسقف والأرضيات | ○ | ○ | ○ | ○ | ○ |
| Conductivity of materials مدى قلة توصيل الحرارة في المواد المستخدمة لبناء الغلاف الخارجي للمبنى | ○ | ○ | ○ | ○ | ○ |
| Resistance of the materials مدى مقاومة الحرارة للمواد المستخدمة في بناء الغلاف الخارجي للمبنى | ○ | ○ | ○ | ○ | ○ |
| Type of Insulation materials نوع ومدى فعالية العوازل الحرارية المستخدمة | ○ | ○ | ○ | ○ | ○ |

***10. الجدران الخارجية: وتحتوي على أنواع مختلفه من مواد البناء المستخدمة. الرجاء قيم مواد البناء التالية التي تستخدم في الجدران الخارجية لغرض ترشيد الطاقة الكهربائية في المباني**

**External walls: This involves multiple types of construction materials used for external walls. Please assess the techniques below from an energy reduction perspective.**

| | ليست مهمة Not important | قليلة الأهمية Less important | مهمة Important | مهمًا Very important | فائقة الأهمية Extremely important |
|---|---|---|---|---|---|
| Design external walls with Mud in order to be highly insulated إستخدام مادة الطين في الجدران الخارجية لغرض رفع فاعلية العزل الحراري | ○ | ○ | ○ | ○ | ○ |
| Design external walls with solid Red- clay brick إستخدام الطوب الأحمر الصلب الغير مفرغ أو الطوب الفخاري في الجدران الخارجية لغرض رفع فاعلية العزل الحراري | ○ | ○ | ○ | ○ | ○ |
| Use Wood materials for external walls to increase their insulation إستخدام الخشب كأحد عناصر بناء الجدران الخارجية لغرض رفع فاعلية العوازل الحرارية | ○ | ○ | ○ | ○ | ○ |
| Use Stone built external walls تصميم الجدران الخارجية لتكون مبنية بالحجر الصلب لغرض رفع كفائة فاعلية العزل الحراري | ○ | ○ | ○ | ○ | ○ |
| Use cavity techniques in external walls أستخدام تقنية الفراغات الداخلية مع الطين او الطوب العازل لغرض رفع كفائة فاعلية العزل الحراري للجدران الخارجية | ○ | ○ | ○ | ○ | ○ |

***11. الشبابيك الخارجية تحتوي على أنواع مختلفة من تقنيات وتصاميم الزجاج. قيم التقنيات التالية لغرض ترشيد إستهلاك الطاقة الكهربائية في المباني**

**External windows: This contains multiple types of glazing design techniques. Please assess the techniques below that reduce energy demand**

| | ليست مهمة Not important | قليلة الأهمية Less important | مهمة Important | مهمًا Very important | فائقة الأهمية Extremely important |
|---|---|---|---|---|---|
| Increase the thickness of glazing زيادة سماكة الزجاج في الشبابيك | ◯ | ◯ | ◯ | ◯ | ◯ |
| Use double or triple glazing with air between glazing panels إستخدام زجاج طبقتين أو ثلاث طبقات مع غاز الهواء بينها لغرض رفع كفائة العزل الحراري | ◯ | ◯ | ◯ | ◯ | ◯ |
| Use double or triple glaze with argon gas between glazing panels إستخدام طبقتين أو ثلاث طبقات من الزجاج مع غاز الأرجون بينها لغرض رفع كفائة العزل الحراري | ◯ | ◯ | ◯ | ◯ | ◯ |
| Use highly air tight windows تصميم الشبابيك الخارجية مع إحكام تسرب الهواء | ◯ | ◯ | ◯ | ◯ | ◯ |

***12. أسقف (الأسطح) المباني المتضمنة مواد البناء المستخدمة له دور في ترشيد إستهلاك الطاقة الكهربائية في المباني. قيم التقنيات التالية لغرض ترشيد إستهلاك الطاقة الكهربائية**

**Efficient Roof: This includes the roof construction materials. Please assess the list of techniques below that reduce energy consumption.**

| | ليست مهمة Not important | قليلة الأهمية Less important | مهمة Important | مهمًا Very important | فائقة الأهمية Extremely important |
|---|---|---|---|---|---|
| Design the external roof above the structure concrete with rain insulation and wood materialsتصميم الأسقف الخارجية للمباني لتكون مواد عازلة للمطر ومادة الخشب فوق الخرسانة المسلحة | ◯ | ◯ | ◯ | ◯ | ◯ |
| Design the external roofs above the structure concrete by efficient insulation materials and concrete tilesتصميم الأسقف الخارجية بمواد عازلة حرارية فوق الخرسانة المسلحة وبلاط | ◯ | ◯ | ◯ | ◯ | ◯ |
| Design the external roofs above the structure concrete by green grass to increase the insulationتصميم الأسقف الخارجية بعد الخرسانة المسلحة بزراعة الأعشاب الخضراء لتزيد من كفائة العزل الحراري | ◯ | ◯ | ◯ | ◯ | ◯ |
| Create a cavity above the structure, ventilated at night to prevent sun direct heat تصميم الأسقف الخارجية بعمل فجوة بين الخرسانة المسلحة وأرضية السطح لمرور تيار هوائي لغرض إمتصاص حرارة أشعة الشمس | ◯ | ◯ | ◯ | ◯ | ◯ |

***13. التصميم المقاوم الفعال لأرضية المبنى له دور في ترشيد إستهلاك الطاقة والتي تتضمن المواد المستخدمة في البناء بعد الخرسانات والقواعد الإنشائية. قيم التقنيات التالية المتعلقة في تصميم طبقات أرضية المباني لغرض ترشيد الطاقة الكهربائية**

**Efficient Floor (in addition to the basement structure): this includes the used construction materials on the floor. Please assess the techniques below from an energy reduction perspective**

| | ليست مهمة Not important | قليلة الأهمية Less important | مهمة Important | مهمًا Very important | فائقة الأهمية Extremely important |
|---|---|---|---|---|---|
| Use mud insulation, mortar and concrete tiles أستخدام مواد الطين العازل والبلاط في الأرضيات | ○ | ○ | ○ | ○ | ○ |
| Use wood insulation materials أستخدام الخشب كنوع من العوازل في الأرضيات | ○ | ○ | ○ | ○ | ○ |
| Use thick layer of sand and concrete tiles أستخدام طبقة سميكة من الرمل والبلاط | ○ | ○ | ○ | ○ | ○ |
| Use layer of concrete including sand and concrete tiles أستخدام طبقة إضافية من الخرسانة المسلحة المخلوطة مع الرمل ثم البلاط كنوع من العوازل | ○ | ○ | ○ | ○ | ○ |

***14. المعايير التالية أدناه هي معايير جديدة متخصصة في المواد المستخدمة للبناء في الغلاف الخارجي تم إدراجها بناءاً على توصية الخبراء في المرحلة السابقة من الدراسة. الرجاء قيم المعايير أدناه بناء على خبرتك العلمية والعملية**

**Below are further new criteria which have been added, based on experts' participation. Please assess these criteria on the basis of your own experience.**

| | ليست مهمة Not important | قليلة الأهمية Less important | مهمة Important | مهمًا Very important | فائقة الأهمية Extremely important |
|---|---|---|---|---|---|
| Use modern construction materials which have high insulation and are available in the country أستخدام مواد بناء حديثة متوفرة في البلد وتحتوي على عزل حراري عالي | ○ | ○ | ○ | ○ | ○ |
| Use a suitable construction material in terms of coolness retention أستخدام مواد بناء مناسبة بخصوص حفظ البرودة داخل المبنى | ○ | ○ | ○ | ○ | ○ |
| Use volcanic bricks as an efficient construction material أستخدام الطوب البركاني كأحد عناصر مواد البناء في الغلاف الخارجي للمبنى | ○ | ○ | ○ | ○ | ○ |
| Use double skin walls in designing the external walls أستخدام عدة طبقات في تصميم الجدران الخارجية للمبنى | ○ | ○ | ○ | ○ | ○ |
| Use foam glazing in external windows أستخدام نوع الزجاج العاتم للشبابيك الخارجية | ○ | ○ | ○ | ○ | ○ |
| Use plaster for glaze insulation for external windows أستخدام اللواصق العازل للزجاج الخارجي للشبابيك | ○ | ○ | ○ | ○ | ○ |
| Use natural stone in floors أستخدام الحجر الطبيعي لتصميم أرضيات المبنى | ○ | ○ | ○ | ○ | ○ |

## Section Three: On-site renewable energy and cultural image تقنية الطاقة ال...

في هذا الجزء هناك معايير وأستراتيجيات تساهم في ترشيد الطاقة في المباني . هذه المعايير متعلقة في الطاقة المتجددة والصورة الأجتماعية في المملكة العربية السعودية. [illegible]
الرجاء ساهم في تقييم المعايير أدناه حسب خبرتك العلمية والعملية

In this part of questionnaire, there are many other different design strategies and criteria have been added based on experts' feedback. Pleas assess each criteria individually based on your experience

***15. توليد الطاقة الكهربائية عن طريق أستخدام شرائح الطاقة الشمسية: هناك طرق مختلفة لتحويل الطاقة الشمسية إلى طاقة كهربائية. قيم الطرق والتقنيات التالية بناءا على خبرتك**

**Energy generation using (Photovoltaic PV): There are multiple ways of using PV in buildings. Based on your experience please assess the efficient ways that can generate more electricity**

| | ليست مهمة Not important | قليلة الأهمية Less important | مهمة Important | مهمًا Very important | فائقة الأهمية Extremely important |
|---|---|---|---|---|---|
| Use the PV on top of the building oriented south facing تركيب الشرائح الشمسية في أعلى المبنى وتوجيهها إلى أتجاه الجنوب | ○ | ○ | ○ | ○ | ○ |
| Use the PV on top of the building oriented east and west facing تركيب الشرائح الشمسية في أعلى المبنى وتوجيهها بأتجاهي الشرق والغرب | ○ | ○ | ○ | ○ | ○ |
| PV on external windows تركيب الشرائح الشمسية على الشبابيك الخارجية | ○ | ○ | ○ | ○ | ○ |
| Use solar wall techniques أستخدام تقنية توليد الطاقة الشمسية عن طريق الجدران الخارجية | ○ | ○ | ○ | ○ | ○ |

***16. الرجاء قم بتقييم التقنيات التالية المتعلقة بالإستخدامات الأجتماعية للغرف لغرض ترشيد الطاقة في المباني السكنية**

**Social/cultural image: Please assess the techniques below in terms of energy saving related to room usage**

| | ليست مهمة Not important | قليلة الأهمية Less important | مهمة Important | مهمًا Very important | فائقة الأهمية Extremely important |
|---|---|---|---|---|---|
| Reduce area of rooms that have highest use period (e.g. bed rooms) تقليل مساحات الغرف الأكثر إستخدام مثل غرف النوم | ○ | ○ | ○ | ○ | ○ |
| o Use the second floor of the building for rooms that have less usage period (e.g guest rooms) and use the ground floor for rooms that have high usage period(e.g. bed room of sitting area) تصميم المبنى ليكون إستخدام الطابق الثاني للغرف الأقل إستخدام مثل صلات الضيوف وإستخدام الغرف في الطابق الأرضي للغرف الأكثر إستخدام لترشيد إستهلاك الطاقة | ○ | ○ | ○ | ○ | ○ |
| As the underground is cooler, use the underground level instead of the over ground levels أستخدام أدوار تحت الأرض بدلاً من الادوار فوق الأرض | ○ | ○ | ○ | ○ | ○ |
| Use layer of concrete including sand and concrete tiles أستخدام طبقة إضافية من الخرسانة المسلحة المخلوطة مع الرمل ثم البلاط كنوع من العوازل | ○ | ○ | ○ | ○ | ○ |

**✱17. المعايير التالية أدناه هي معايير جديدة متخصصة في الطاقة المتجددة والصورة الأجتماعية مضافة بناءاً على توصية الخبراء في المرحلة السابقة من الدراسة. الرجاء قيم المعايير ادناه بناء على خبرتك العلمية والعملية**

**Below are further new criteria which have been added, based on experts' participation. Please assess these criteria on the basis of your own experience.**

| | ليست مهمة Not important | قليلة الأهمية Less important | مهمة Important | مهمًا Very important | فائقة الأهمية Extremely important |
|---|---|---|---|---|---|
| Use wind energy generation أستخدام الطاقة المتجددة من الرياح في الموقع | ○ | ○ | ○ | ○ | ○ |
| Use new and efficient PV available on the market أستخدام الشرائح الشمسية الجديدة الفعالة المتوفرة في الأسواق | ○ | ○ | ○ | ○ | ○ |
| Heat the DHW by solar radiation تسخين المياة في المبنى عن طريق الأشعاع الشمسي | ○ | ○ | ○ | ○ | ○ |
| Eliminate the use of an exterior annex for guests or housemaids and drivers, as such a structure consumes more energy because of being totally exposed to harsh climatic conditions ألغاء الغرف والمرافق الخارجية مثل الملاحق وغرف السائقين لانها تتعرض لضروف مناخية قاسية | ○ | ○ | ○ | ○ | ○ |
| Reduce unnecessary spaces which add no value in the building تقليل المساحات التي ليست ضرورية في الغرف داخل المبنى | ○ | ○ | ○ | ○ | ○ |

هنا نهاية الإستفتاء. شكراً لمشاركتكم. الرجاء اضغط
(Done)

نايف بن علي الدوسري
طالب دكتوراة في الهندسة المعمارية والبناء
الإستدامة في المباني وترشيد الطاقة
جامعة كاردف
بريطانيا

This is the end of the questionnaire. Thank you for your participation. Pleas click (Done)

Naief A. Aldossary
Ph.D Candidate in Architectural Engineering and Construction
Cardiff School of Engineering
Cardiff University
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United Kingdom

# APPENDIX D- Experts consultations- Questionnaire samples (Round three)

## introduction مقدمة

سعادة الخبير

أشكرك جزيل الشكر على مساهمتك في المرحلتين السابقتين للدراسة ونسأل الله لنا ولكم التوفيق وأن يكتب لكم أجرها. في الاستطلاع السابق كان هناك تضارب واختلاف في وجهات النظر بين أراء الخبراء في بعض المعايير التصميمية.

هذا الاستبيان شبية بالسابق لكن مدعم وموضح فيه متوسط أراء بقية الخبراء في المعايير التصميمية

توضيح متوسط أراء بقية الخبراء يساعدك في أختيار المعيار المناسب مما يساعد للوصول للإجماع بين الخبراء في التقييم

أنت أحد الخبراء المشاركين في الدراسة والمساهمين في المرحلتين الأولى والثانية وأرجو مساهمتك في هذا الأستبيان للمرحلة الأخيرة كي تصل لأجماع نهائي بين الخبراء.
[illegible] . هذا الأستطلاع لن يستغرق أكثر من 10 دقائق من وقتكم الثمين

سائلين المولى التوفيق

Dear Expert,

Firstly I would like to thank you for your participation in the past two rounds and for your useful feedback and comments in support of the study. As mentioned initially, three rounds are needed to reach expert consensus on each criterion. In the recent consultation on the questionnaire, expert consensus was not reached regarding some design criteria.

This questionnaire is similar to that of the second round, but includes statistical information about average rating of the expert decisions to support your final rating decision.

Your answers will be helpful in evaluating potential design factors for sustainable domestic buildings in Saudi Arabia. It will take approximately 10 minutes to respond to the questionnaire, and your individual privacy, as well as the confidentiality of the information provided, will be maintained in all published and written data analysis resulting from the study.

*** الرجاء أكتب بياناتك الشخصية Please type your demographic information**

Name :الإسم

Organization :جهة العمل

Email address :البريد الألكتروني

Section One: Architectural Design القسم الأول- التصميم المعماري

تم توضيح متوسط رأي الخبراء في المرحلة السابقة لكل معيار لتساعدك في أختيار التقييم المناسب

**التصميم المعماري للمبنى يلعب دور كبير في ترشيد الطاقة الكهربائية. الرجاء قيم التقنيات المختلفة التالية لغرض ترشيد الطاقة في المبنى Efficient Architectural design plays a significant role for energy saving. Please assess the techniques from the list below that can reduce the energy demand** *

| | ليست مهمة Not Important (1) | قليلة الأهمية Less Important (2) | مهمة Important (3) | مهمًا Very important (4) | فائقة الأهمية Extremely important (5) |
|---|---|---|---|---|---|
| (Orientation of the building south facing- Average Rating 3.29) إتجاه المبنى للناحية الجنوبية - متوسط رأي الخبراء 3.29 | ○ | ○ | ○ | ○ | ○ |
| (Shading devices- Average Rating 4.19) توزيع الضل حول المبنى - متوسط رأي الخبراء 4.19 | ○ | ○ | ○ | ○ | ○ |
| (Minimizing building size as possible- Average Rating 3.27) تقليل حجم المبنى بقدر الإمكان - متوسط رأي الخبراء 3.27 | ○ | ○ | ○ | ○ | ○ |
| (Optimal design of building shape- Average Rating 4.30) التصميم الفعال لشكل المبنى - متوسط رأي الخبراء 4.30 | ○ | ○ | ○ | ○ | ○ |
| (Internal subdivisions of the building- Average Rating 3.47) التقسيمات الداخلية للمبنى - متوسط رأي الخبراء 3.47 | ○ | ○ | ○ | ○ | ○ |

## Section One: Architectural Design القسم الأول- التصميم المعماري

تم توضيح متوسط رأي الخبراء في المرحلة السابقة لكل معيار لتساعدك في اختيار التقييم المناسب

*** شكل المبنى أحد معايير التصميم المعماري التي تتحكم في إستهلاك الطاقة: الرجاء قيم التقنيات التالية لغرض ترشيد إستهلاك الطاقة في المباني Building shape: Please assess the techniques mentioned below as to their capacity to reduce energy demand in domestic buildings**

| | ليست مهمة Not Important (1) | قليلة الأهمية Less Important (2) | مهمة Important (3) | مهمًا Very important (4) | فائقة الأهمية Extremely important (5) |
|---|---|---|---|---|---|
| (Slope shape to minimize to exposure sun heat - Average Rating 3.56 (تصميم المبنى لتكون بالأسطح المائلة لتقليل مواجهة حرارة الشمس - متوسط رأي الخبراء 3.56 | ○ | ○ | ○ | ○ | ○ |
| (Use green building techniques - Average Rating 4.25) أستخدام تقنية الأسطح الخضراء - متوسط رأي الخبراء 4.25 | ○ | ○ | ○ | ○ | ○ |

*** تصميم الشبابيك الخارجية له دور في أستهلاك الطاقة: الرجاء قيم التقنيات التالية من ناحية ترشيد الطاقة الكهربائية في المباني Please assess from the list below of windows' design techniques in term of energy saving**

| | ليست مهمة Not Important (1) | قليلة الأهمية Less Important (2) | مهمة Important (3) | مهمًا Very important (4) | فائقة الأهمية Extremely important (5) |
|---|---|---|---|---|---|
| (Reduce windows area - Average Rating 3.93) تقليل مساحات الشبابيك الخارجية بقدر الإمكان- متوسط رأي الخبراء 3.93 | ○ | ○ | ○ | ○ | ○ |
| (Reduce the number of windows - Average Rating 3.60) تقليل عدد الشبابيك الخارجية بقدر الامكان - متوسط رأي الخبراء 3.60 | ○ | ○ | ○ | ○ | ○ |
| (Use canopies on top of windows to prevent from sun heat - Average Rating 4.17) تركيب مظلات خارجة فوق الشبابيك لتمنع وصول حرارة الشمس - متوسط رأي الخبراء 4.17 | ○ | ○ | ○ | ○ | ○ |
| (Grow grass in the front of each window - Average Rating 3.15) زراعة أعشاب خضراء أمام كل شباك - متوسط رأي الخبراء 3.15 | ○ | ○ | ○ | ○ | ○ |

**توزيع الظل حول المبنى له دور في ترشيد الطاقة الكهربائية: الرجاء قيم التقنيات التالية المتعلقة بأساليب توزيع الظل لغرض ترشيد الطاقة الكهربائية في المباني Shading device: Please assess the techniques below of shading design in terms of energy efficiency** *

| | ليست مهمة Not Important (1) | قليلة الأهمية Less Important (2) | مهمة Important (3) | مهمًا Very important (4) | فائقة الأهمية Extremely important (5) |
|---|---|---|---|---|---|
| (Use high shading devices around the building on top of external walls - Average Rating 3.44) أستخدام مظلات عالية فوق الجدران الخارجية لتوفير ظل حول المبنى - متوسط رأي الخبراء 3.44 | ○ | ○ | ○ | ○ | ○ |
| (Use internal and/or external shutter for windows to prevent unwanted solar gains - Average Rating 3.83) أستخدام ستائر داخلية وخارجية للشبابيك لتقليل حرارة الشمس - متوسط رأي الخبراء 3.83 | ○ | ○ | ○ | ○ | ○ |
| (Use efficient court yard landscaping design to provide shade around the building - Average Rating 4.13) تصميم حديقة في الفناء الخارجي لتوزيع الظل حول المبنى - متوسط رأي الخبراء 4.13 | ○ | ○ | ○ | ○ | ○ |
| (Use horizontal canopy to create shade - Average Rating 3.91) أستخدام مظلات أفقية لتوفير ظل عندما تكون الشمس عمودية - متوسط رأي الخبراء 3.91 | ○ | ○ | ○ | ○ | ○ |

**نظام التكييف والتهوية له دور كبير في إستهلاك الطاقة: الرجاء قيم التقنيات التالية المتعلقة بأساليب التكييف أو التدفئة لغرض تقليل إستهلاك الطاقة الكهربائية في المباني HVAC: Please assess the list of techniques below related to cooling and/ or heating from an energy saving perspective** *

| | ليست مهمة Not Important (1) | قليلة الأهمية Less Important (2) | مهمة Important (3) | مهمًا Very important (4) | فائقة الأهمية Extremely important (5) |
|---|---|---|---|---|---|
| (Divide the internal rooms in the building into zones to create separate cooling and/ or heating units and use rooms when the need arises only - Average Rating 3.98) تقسيم المبنى من الداخل إلى مناطق أو وحدات لتكون كل وحدة نظام تكييف مستقل- متوسط رأي الخبراء 3.98 | ○ | ○ | ○ | ○ | ○ |
| (Use sensors for air conditioning that control temperature of the rooms - Average Rating 4.16) - أستخدام حساسات للتحكم في درجة حرارة الغرف متوسط رأي الخبراء 4.16 | ○ | ○ | ○ | ○ | ○ |
| (Use mechanical ventilation techniques - Average Rating 3.85) أستخدام تقنيات التهوية الميكانيكية - متوسط رأي الخبراء 3.85 | ○ | ○ | ○ | ○ | ○ |
| (Use ground heat exchange techniques - Average Rating 3.38) أستخدام تقنيات التبريد من خلال مرور الهواء من داخل الأرض - متوسط رأي الخبراء 3.38 | ○ | ○ | ○ | ○ | ○ |

**التهوية الطبيعية تساهم في ترشيد الطاقة للمباني: الرجاء قيم الخيارات التالية للتهوية الطبيعية التي تساهم في ترشيد الطاقة الكهربائية للمباني Natural ventilation: Please assess the list of ventilation techniques below from an energy reduction perspective** *

| | ليست مهمة Not Important (1) | قليلة الأهمية Less Important (2) | مهمة Important (3) | مهمًا Very important (4) | فائقة الأهمية Extremely important (5) |
|---|---|---|---|---|---|
| (Use an efficient windows design to ventilate the building - Average Rating 3.15) تصميم شبابيك فعالة لتهوية المبنى - متوسط رأي الخبراء 3.15 | ○ | ○ | ○ | ○ | ○ |
| (Use ventilation tower technique to create air shafts/stacks - Average Rating 3.62) أستخدام تقنية التهوية الطبيعية عن طريق أبراج التهوية والمداخن في المبنى - متوسط رأي الخبراء 3.62 | ○ | ○ | ○ | ○ | ○ |
| (Design the indoor of the building by open plan in order to provide interior airflow - Average Rating 3.96) تصميم المبنى من الداخل لتكون مفتوحة وتسهل تدفق التيار الهوائي - متوسط رأي الخبراء 3.96 | ○ | ○ | ○ | ○ | ○ |
| (Each room should be designed to have two opening windows to promote air flow - Average Rating 3.13) كل غرفة يجب أن تحتوي على شباكين مفتوحة لتوفير تيار هوائي - متوسط رأي الخبراء 3.13 | ○ | ○ | ○ | ○ | ○ |

**المعايير التالية أدناه هي معايير جديدة مضافة بناءاً على توصية الخبراء في المرحلة السابقة من الدراسة. الرجاء قيم المعايير ادناه بناء على خبرتك العلمية والعملية Below are the many new criteria which have been added, based on experts' participation. Please assess these criteria on the basis of your own experience.** *

| | ليست مهمة<br>Not Important (1) | قليلة الأهمية<br>Less Important (2) | مهمة<br>Important (3) | مهمًا<br>Very important (4) | فائقة الأهمية<br>Extremely important (5) |
|---|---|---|---|---|---|
| (Place windows in the wall in order to have natural light and air stock - Average Rating 4.18) وضع الشبابيك في أماكن التي تسهل مرور أكثر للتيار الهوائي والأضائة الطبيعية - متوسط رأي الخبراء 4.18 | ○ | ○ | ○ | ○ | ○ |
| (Use colour glaze for external windows - Average Rating 3.49) أستخدام زجاج ملون للشبابك الخارجية للمبنى - متوسط رأي الخبراء 3.49 | ○ | ○ | ○ | ○ | ○ |
| (Design the building so as to have space inside which will support the natural ventilation - Average Rating 4.07) تصميم المبنى ليحتوي على فراغات داخلية مفتوحة لتدعم التهوية الطبيعية - متوسط رأي الخبراء 4.07 | ○ | ○ | ○ | ○ | ○ |
| (Place the windows in the north side, with solar collection in the south face - Average Rating 3.89) تخصيص الشبابيك في الواجهة الشمالية بينما الشرائح الشمسية في الواجهة الجنوبية - متوسط رأي الخبراء 3.89 | ○ | ○ | ○ | ○ | ○ |
| (Orient the building to the north to provide ventilation and avoid solar heat - Average Rating 4.09) توجية المبنى للأتجاه الشمالي لتسهل عملية التهوية الطبيعية ولتجنب الأشعاع الشمسي - متوسط رأي الخبراء 4.09 | ○ | ○ | ○ | ○ | ○ |
| (Place natural skylight windows in the roof - Average Rating 3.05) وضع شبابيك على سقف المبنى لتوفير أضائة طبيعية - متوسط رأي الخبراء 3.05 | ○ | ○ | ○ | ○ | ○ |
| (Use Semi-detached or Terraced house configuration - Average Rating 3.24) 3.24 أستخدام تقنية المباني المتلاصقة - متوسط رأي الخبراء | ○ | ○ | ○ | ○ | ○ |
| (Reduce the size and number of southern windows - Average Rating 3.70) تقليل عدد ومساحة الشبابيك في الواجهة الجنوبية متوسط رأي الخبراء 3.70 - | ○ | ○ | ○ | ○ | ○ |
| (Reduce the number of windows on the east and west sides - Average Rating 3.11) تقليل عدد الشبابيك في الأتجاهين الشرقي والغربي - متوسط رأي الخبراء 3.11 | ○ | ○ | ○ | ○ | ○ |
| (Use light colours for external walls - Average Rating 4.17) أستخدام الوان فاتحة للجدران الخارجية - متوسط رأي الخبراء 4.17 | ○ | ○ | ○ | ○ | ○ |
| (Increase green areas around the building - Average Rating 4.25) زيادة مساحة المسطحات الخضراء حول المبنى - متوسط رأي الخبراء 4.25 | ○ | ○ | ○ | ○ | ○ |
| (Use efficient finishing materials with high R-Value - Average Rating 4.59) - أستخدام مواد ذو مقاومة عالية للحرارة في التشطيبات الخارجية للمبنى متوسط رأي الخبراء 4.59 | ○ | ○ | ○ | ○ | ○ |
| (Design the building to take wind direction into account - Average Rating 4.44) تصميم المبنى مع الأخذ في عين الأعتبار أتجاه الرياح لدعم التهوية الطبيعية - متوسط رأي الخبراء 4.44 | ○ | ○ | ○ | ○ | ○ |
| (Consider fitting the building within its surrounding context - | ○ | ○ | ○ | ○ | ○ |

| | | | | | |
|---|---|---|---|---|---|
| Average Rating 4.41) تصميم المبنى ليكون ملائم مع البيئة المحيطة - متوسط رأي الخبراء 4.41 | | | | | |
| (Use sun louver techniques - Average Rating 3.94) أستخدام تقنية تظليل الشبابيك الخارجية عن طريق فتحات صغيرة ورواشين - متوسط رأي الخبراء 3.94 | ○ | ○ | ○ | ○ | ○ |
| (Shading in Ventilated Facades - Average Rating 4.11) أستخدام تقنية الظل والتهوية على كامل واجهة المبنى - متوسط رأي الخبراء 4.11 | ○ | ○ | ○ | ○ | ○ |
| (Use planting shades instead of steel shades in windows - Average Rating 4.04) ستخدام الزراعة لتوفير الظل بدلاً من الحديد - متوسط رأي الخبراء 4.04 | ○ | ○ | ○ | ○ | ○ |
| (Use sun reflection design techniques - Average Rating 3.74) أستخدام تقنية أنعكاس ضوء الشمس في التصميم - متوسط رأي الخبراء 3.74 | ○ | ○ | ○ | ○ | ○ |
| (Reduce the width of the south facing “façade” as much as possible - Average Rating 3.58) تقليل عرض الواجهة الجنوبية بقدر المستطاع - متوسط رأي الخبراء 3.85 | ○ | ○ | ○ | ○ | ○ |
| (Employ Building Management Systems (BMS) to control the lighting for the whole building - Average Rating 3.83) أستخدام أنظمة أدارة المباني للتحكم في الأضائة - متوسط رأي الخبراء 3.83 | ○ | ○ | ○ | ○ | ○ |
| (Use roof shading techniques- Average Rating 3.89) أستخدام تقنية الضل في الأسطح - متوسط رأي الخبراء 3.89 | ○ | ○ | ○ | ○ | ○ |

## Section Two: Building Fabric الغلاف الخارجة للمبنى - مواد البناء المستخدمة

تم توضيح متوسط رأي الخبراء في المرحلة السابقة لكل معيار لتساعدك في أختيار التقييم المناسب

*** بشكل عام: قيم الطرق الفعالة التالية التي لها تأثير في ترشيد الطاقة الكهربائية في المباني عن طريق المواد المستخدمة للبناء للغلاف الخارجي Generally, please assess building envelope efficient factors that reduce energy demand**

| | ليست مهمة Not Important (1) | قليلة الأهمية Less Important (2) | مهمة Important (3) | مهمًا Very important (4) | فائقة الأهمية Extremely important (5) |
|---|---|---|---|---|---|
| (Thicknesses of house Envelop - Average Rating 4.09)سماكة الجدران الخارجية والأسقف والأرضيات - متوسط رأي الخبراء 4.09 | ○ | ○ | ○ | ○ | ○ |
| (Low conductivity of materials - Average Rating 4.40) مدى قلة توصيل الحرارة للمواد البناء المستخدمة للغلاف الخارجي للمبنى - متوسط رأي الخبراء 4.40 | ○ | ○ | ○ | ○ | ○ |
| (Resistance of the materials - Average Rating 4.44) مدى مقاومة الحرارة للمواد البناء المستخدمة للغلاف الخارجي للمبنى - متوسط رأي الخبراء 4.44 | ○ | ○ | ○ | ○ | ○ |
| (Type of Insulation materials - Average Rating 4.67) نوع ومدى فعالية العوازل الحرارية المستخدمة - متوسط رأي الخبراء 4.67 | ○ | ○ | ○ | ○ | ○ |

*** الجدران الخاريجة: وتحتوي على أنواع مختلفه من مواد البناء المستخدمة. الرجاء قيم مواد البناء التالية التي تستخدم في الجدران الخارجية لغرض ترشيد الطاقة الكهربائية في المباني External walls: This involves multiple types of construction materials used for external walls. Please assess the techniques below from an energy reduction perspective.**

| | ليست مهمة Not Important (1) | قليلة الأهمية Less Important (2) | مهمة Important (3) | مهمًا Very important (4) | فائقة الأهمية Extremely important (5) |
|---|---|---|---|---|---|
| (Design external walls with Mud in order to be highly insulated - Average Rating 3.09) أستخدام مادة الطين في الجدران الخارجية لغرض رفع كفائة اعزل الحراري - متوسط رأي الخبراء 3.09 | ○ | ○ | ○ | ○ | ○ |
| (Design external walls with solid Red- clay brick - Average Rating 3.64) أستخدام الطوب الأحمر الصلب الغير مفرغ أو الطوب الفخاري في الجدران الخارجية لغرض رفع كفائة العزل الحراري - متوسط رأي الخبراء 3.64 | ○ | ○ | ○ | ○ | ○ |
| (Use Stone built external walls - Average Rating 3.15) أستخدام الحجر الصلب في الجدران الخارجية لغرض رفع كفائة العزل الحراري متوسط رأي الخبراء 3.15 - | ○ | ○ | ○ | ○ | ○ |
| (Use cavity techniques in external walls - Average Rating 3.81) أستخدام تقنية الفراغات الداخلية في الطوب المستخدم لغرض رفع كفائة العزل الحراري - متوسط رأي الخبراء 3.81 | ○ | ○ | ○ | ○ | ○ |

***الشبابيك الخارجية تحتوي على أنواع مختلفة من تقنيات وتصاميم الزجاج. قيم التقنيات التالية لغرض ترشيد إستهلاك الطاقة الكهربائية في المباني External windows: This contains multiple types of glazing design techniques. Please assess the techniques below that reduce energy demand**

| | ليست مهمة Not Important (1) | قليلة الأهمية Less Important (2) | مهمة Important (3) | مهمًا Very important (4) | فائقة الأهمية Extremely important (5) |
|---|---|---|---|---|---|
| (Increase the thickness of glazing - Average Rating 3.63(زيادة سماكة الزجاج في الشبابيك - متوسط رأي الخبراء 3.63 | ○ | ○ | ○ | ○ | ○ |
| (Use double or triple glazing with air between glazing panels - Average Rating 4.17) أستخدام زجاج طبقتين أو ثلاث طبقات مع غاز الهواء بينهم لغرض رفع كفائة العزل الحراري - متوسط رأي الخبراء 4.17 | ○ | ○ | ○ | ○ | ○ |
| (Use double or triple glaze with argon gas between glazing panels - Average Rating 3.85(أستخدام زجاج طبقتين أو ثلاث طبقات مع غاز الأرجون بينهم لغرض رفع كفائة العزل الحراري - متوسط رأي الخبراء 3.85 | ○ | ○ | ○ | ○ | ○ |
| (Use highly air tight windows - Average Rating 4.32) تصميم الشبابيك الخارجية مع أحكام تسرب الهواء - متوسط رأي الخبراء 4.32 | ○ | ○ | ○ | ○ | ○ |

***أسقف (الأسطح) المباني المتضمنة مواد البناء المستخدمة له دور في ترشيد إستهلاك الطاقة الكهربائية في المباني. قيم التقنيات التالية لغرض ترشيد إستهلاك الطاقة الكهربائية Efficient Roof: This includes the roof construction materials. Please assess the list of techniques below that reduce energy consumption.**

| | ليست مهمة Not Important (1) | قليلة الأهمية Less Important (2) | مهمة Important (3) | مهمًا Very important (4) | فائقة الأهمية Extremely important (5) |
|---|---|---|---|---|---|
| (Design the external roof above the structure concrete with rain insulation and wood materials - Average Rating 3.20) تصميم الأسقف الخارجية لتكون مواد عازلة للمطر ومادة الخشب فوق الخرسانة المسلحة - متوسط رأي الخبراء 3.20 | ○ | ○ | ○ | ○ | ○ |
| (Design the external roofs above the structure concrete by efficient insulation materials and concrete tiles - Average Rating 4.28) تصميم الأسقف الخارجية بمواد عازلة حرارية فوق الخرسانة المسلحة وبلاط - متوسط رأي الخبراء 4.28 | ○ | ○ | ○ | ○ | ○ |
| (Design the external roofs above the structure concrete by green grass to increase the insulation - Average Rating 3.89) تصميم الأسقف الخارجية بعد الخرسانة المسلحة بزراعة الاعشاب الخضراء لتزيد من كفائة العزل الحراري - متوسط رأي الخبراء 3.89 | ○ | ○ | ○ | ○ | ○ |
| (Create a cavity above the structure, ventilated at night to prevent sun direct heat - Average Rating 3.74) تصميم الأسقف الخارجية بعمل فجوة بين الخرسانة المسلحة وأرضية السطح لمرور تيار هوائي وأمتصاص حرارة الشمس - متوسط رأي الخبراء 3.74 | ○ | ○ | ○ | ○ | ○ |

***التصميم المقاوم الفعال لأرضية المبنى له دور في ترشيد إستهلاك الطاقة والتي تتضمن المواد المستخدمة في البناء بعد الخرسانات والقواعد الإنشائية. قيم التقنيات التالية المتعلقة في تصميم طبقات أرضية المباني لغرض ترشيد الطاقة الكهربائية Efficient Floor (in addition to the basement structure): this includes the used construction materials on the floor. Please assess the techniques below from an energy reduction perspective**

| | ليست مهمة Not Important (1) | قليلة الأهمية Less Important (2) | مهمة Important (3) | مهمًا Very important (4) | فائقة الأهمية Extremely important (5) |
|---|---|---|---|---|---|
| (Use mud insulation, mortar and concrete tiles - Average Rating 3.35) أستخدام الطين العازل والبلاط في الأرضيات - متوسط رأي الخبراء 3.35 | ○ | ○ | ○ | ○ | ○ |
| (Use wood insulation materials - Average Rating 3.16) أستخدام الخشب كنوع من العوازل في الأرضيات - متوسط رأي الخبراء 3.16 | ○ | ○ | ○ | ○ | ○ |
| (Use thick layer of sand and concrete tiles - Average Rating 3.38) أستخدام طبقة سميكة من الرمل وبلاط خرساني - متوسط رأي الخبراء 3.38 | ○ | ○ | ○ | ○ | ○ |
| (Use layer of concrete including sand and concrete tiles - Average Rating 3.29) أستخدام طبقة أضافية من الخرسانة مع رمل وبلاط خرساني كنوع من العوازل - متوسط رأي الخبراء 3.29 | ○ | ○ | ○ | ○ | ○ |

**المعايير التالية أدناه هي معايير جديدة متخصصة في المواد المستخدمة للبناء في الغلاف الخارجي تم إدراجها بناءاً على توصية الخبراء في المرحلة السابقة من الدراسة. الرجاء قيم المعايير أدناه بناء على خبرتك العلمية والعملية Below are further new criteria which have been added, based on experts' participation. Please assess these criteria on the basis of your own experience.***

| | ليست مهمة Not Important (1) | قليلة الأهمية Less Important (2) | مهمة Important (3) | مهمًا Very important (4) | فائقة الأهمية Extremely important (5) |
|---|---|---|---|---|---|
| (Use modern construction materials which have high insulation and are available in the country - Average Rating 4.36) توزيع أستخدام مواد بناء حديثة متوفرة في البلد التي تحتوي على كفائة عزل حراري عالي - متوسط رأي الخبراء 4.36 | ○ | ○ | ○ | ○ | ○ |
| (Use a suitable construction material in terms of coolness retention - Average Rating 4.43) أستخدام مواد بناء مناسبة لحفظ البرودة داخل المبنى - متوسط رأي الخبراء 4.43 | ○ | ○ | ○ | ○ | ○ |
| (Use volcanic bricks as an efficient construction material - Average Rating 3.81) أستخدام الطوب البركاني كأحد عناصر مواد البناء للغلاف الخارجي للمبنى - متوسط رأي الخبراء 3.81 | ○ | ○ | ○ | ○ | ○ |
| (Use double skin walls in designing the external walls - Average Rating 3.80) أستخدام عدة طبقات من مواد البناء في تصميم الجدران الخارجية - متوسط رأي الخبراء 3.80 | ○ | ○ | ○ | ○ | ○ |
| (Use foam glazing in external windows - Average Rating 3.64) أستخدام نوع الزجاج المعتم للشبابيك الخارجية - متوسط رأي الخبراء 3.64 | ○ | ○ | ○ | ○ | ○ |
| (Use plaster for glaze insulation for external windows - Average Rating 3.57) أستخدام اللواصق العازلة في زجاج الشبابيك الخارجية للمبنى - متوسط رأي الخبراء 3.57 | ○ | ○ | ○ | ○ | ○ |
| (Use natural stone in floors - Average Rating 3.66) أستخدام الحجر الطبيعي في أرضيات المبنى - متوسط رأي الخبراء 3.66 | ○ | ○ | ○ | ○ | ○ |

Section Three: On-site renewable energy and cultural image تقنية الطاقة ال...

تم توضيح متوسط رأي الخبراء في المرحلة السابقة لكل معيار لتساعدك في أختيار التقييم المناسب

**توليد الطاقة الكهربائية عن طريق أستخدام شرائح الطاقة الشمسية: هناك طرق مختلفة لتحويل الطاقة الشمسية إلى طاقة كهربائية. قيم الطرق والتقنيات التالية بناءاً على خبرتك Energy generation using (Photovoltaic PV): There are multiple ways of using PV in buildings. Based on your experience please assess the efficient ways that can generate more electricity** *

| | ليست مهمة Not Important (1) | قليلة الأهمية Less Important (2) | مهمة Important (3) | مهمًا Very important (4) | فائقة الأهمية Extremely important (5) |
|---|---|---|---|---|---|
| (Use PV on top of the south face of the building - Average Rating 3.71) تركيب الشرائح الشمسية أعلى المبنى وتوجيهها لأتجاه الجنوب - متوسط رأي الخبراء 3.71 | ○ | ○ | ○ | ○ | ○ |
| (Use PV on top of the east and west faces of the building - Average Rating 3.38) تركيب الشرائح الشمسية أعلى المبنى وتوجيهها لأتجاه الشرق والغرب - متوسط رأي الخبراء 3.38 | ○ | ○ | ○ | ○ | ○ |
| (Use solar wall techniques - Average Rating 3.05) تركيب الشرائح الشمسية على الجدران الخارجية - متوسط رأي الخبراء 3.05 | ○ | ○ | ○ | ○ | ○ |

**الرجاء قم بتقييم التقنيات التالية المتعلقة بالإستخدامات الأجتماعية للغرف لغرض ترشيد الطاقة في المباني السكنية Social/cultural image: Please assess the techniques below in terms of energy saving related to room usage** *

| | ليست مهمة Not Important (1) | قليلة الأهمية Less Important (2) | مهمة Important (3) | مهمًا Very important (4) | فائقة الأهمية Extremely important (5) |
|---|---|---|---|---|---|
| (Reduce area of rooms that have highest use period e.g. bed rooms - Average Rating 3.33) تقليل مساحات الغرف الاكثر أستخدام مثل غرف النوم - متوسط رأي الخبراء 3.33 | ○ | ○ | ○ | ○ | ○ |
| ( Use the second floor of the building for rooms that have less usage period (e.g guest rooms) and use the ground floor for rooms that have high usage period e.g. bed room of sitting area - Average Rating 3.47) تصميم المبنى ليكون إستخدام الطابق الثاني للغرف الأقل إستخدام مثل صلات الضيوف وإستخدام الغرف في الطابق الأرضي للغرف الأكثر إستخدام لترشيد إستهلاك الطاقة - متوسط رأي الخبراء 3.47 | ○ | ○ | ○ | ○ | ○ |
| (As the underground is cooler, use the underground level instead of the over ground levels - Average Rating 3.04) أستخدام أدوار تحت الأرض بدلاً من الادوار فوق الأرض - متوسط رأي الخبراء 3.04 | ○ | ○ | ○ | ○ | ○ |

**المعايير التالية أدناه هي معايير جديدة متخصصة في الطاقة المتجددة والصورة الأجتماعية مضافة بناءاً على توصية الخبراء في المرحلة السابقة من الدراسة. الرجاء قيم المعايير ادناه بناء على خبرتك العلمية والعملية Below are further new criteria which have been added, based on experts' participation. Please assess these criteria on the basis of your own experience.***

| | ليست مهمة Not Important (1) | قليلة الأهمية Less Important (2) | مهمة Important (3) | مهمًا Very important (4) | فائقة الأهمية Extremely important (5) |
|---|---|---|---|---|---|
| (Use wind energy generation - Average Rating 3.47) أستخدام الطاقة المتجددة من الرياح في الموقع - متوسط رأي الخبراء 3.47 | ○ | ○ | ○ | ○ | ○ |
| (Use new and efficient PV available on the market - Average Rating 3.64) أستخدام الشرائح الشمسية الجديدة الفعالة المتوفرة في الأسواق - متوسط رأي الخبراء 3.64 | ○ | ○ | ○ | ○ | ○ |
| (Heat the DHW by solar radiation - Average Rating 4.02) تسخين المياة في المبنى عن طريق الأشعاع الشمسي - متوسط رأي الخبراء 4.02 | ○ | ○ | ○ | ○ | ○ |
| (Reduce unnecessary spaces which add no value in the building - Average Rating 4.04) قليل المساحات التي ليست ضرورية في الغرف داخل المبنى - متوسط رأي الخبراء 4.04 | ○ | ○ | ○ | ○ | ○ |

هنا نهاية الإستفتاء. شكراً لمشاركتكم. الرجاء اضغط (Done)

نايف بن علي الدوسري
طالب دكتوراة في الهندسة المعمارية والبناء
الإستدامة في المباني وترشيد الطاقة
جامعة كاردف
بريطانيا

This is the end of the questionnaire. Thank you for your participation. Pleas click (Done)

Naief A. Aldossary
Ph.D Candidate in Architectural Engineering and Construction
Cardiff School of Engineering
Cardiff University
Cardiff- Wales
United Kingdom

## APPENDIX E- Conference Certificate: International Conference on Computing in Civil and Building Engineering Orlando, Florida, United States June 23-25, 2014

UF | Distance & Continuing Education
Conference Department
UNIVERSITY *of* FLORIDA

*Presents this certificate of attendance to:*

***Naief Aldossary***

*For Completion of the*

***15th International Conference on Computing in Civil and Building Engineering (ICCCBE)***

June 23-25, 2014
Orlando, Florida

**APPENDIX F- Conference Certificate: The Seventh Saudi Students Conference (SSC 2014) Edinburgh International Conference Centre (EICC), Edinburgh, The United Kingdom, 1st to 2nd of February 2014.**

# APPENDIX G- IES-VE Certificate

INTEGRATED ENVIRONMENTAL SOLUTIONS

www.iesve.com

## IES Virtual Environment

# Training Certificate

Cost effective, sustainable building design from concept to completion and beyond

This is to certify that

Naief Aldossary

of Cardiff University

attended and completed face-to-face training

in the following **Virtual Environment** software:

| IES VE Product | Date Attended |
|---|---|
| ModelIT & Suncast | 20th March 2012 |
| ApacheSim, ApacheCalc & MacroFlo | 21st March 2012 |

**Hans Dhargalkar**
Training Manager

Integrated Environmental Solutions Ltd