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An Assessment of The Potential of Sustainable Construction in Saudi Arabia With Particular Reference To The City of Mecca

This research is submitted for the PhD Degree to the Civil, Structural, and Environmental Engineering Department of Trinity College Dublin

2017

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Abstract

Global construction industry is growing rapidly. Sustainable principles are applied in the developed world. However, these are absent in the majority of construction in the developing world. Saudi Arabia is the largest construction market in the Middle East therefore, there is an urgent need to consider sustainable construction principles in the country, especially in the major cities like Mecca (with more than one third of the overall Saudi construction).

This research evidenced that there are limited attempts toward achieving sustainable construction across the country. It proposes sustainable solutions based on the literature review, questionnaire survey, personal interviews and the findings of a case study modelling in Mecca. The research also determines potential sustainable techniques suitable for the Saudi Arabian climate based on traditional and historic techniques. This work aims at drawing the attention of government and policy makers towards the importance of sustainability in construction and encouraging sustainable legislation.

A questionnaire survey (distributed to one hundred and twenty-nine key professionals that could demonstrate a sound understanding of construction) and semi-structured interviews, gathered information on current and future sustainable construction practices. According to these, three areas of focus were determined: rammed earth, thermal insulation and solar photovoltaic panels (PVs).

These were applied to a case study building using the Integrated Environmental Solutions -Virtual Environment- (IES-VE) software, which simulates the performance of the building before and after application of the proposed solutions. Simulation showed that the three areas of focus have great potential to enhance sustainability especially when applied simultaneously. The proposed elements could reduce the electricity required by 72 % saving the government about 4,383 USD per year only in

the case study building. The insulated building with rammed earth walls and solar PVs showed the best performance amongst all scenarios. It provided more than the building's cooling energy requirements, which is about 70% of the total building's electricity demand. This scenario is recommended as it also represents the lower embodied energy and operational carbon emissions: there would be a significant reduction in carbon emissions over the lifetime of the building with over a million kilograms of carbon emissions in a period of 20 years (based on a reduction of about more than 50,000 $kgCO_2$ per year).

Furthermore, the model will lead to economic benefits as the governmental subsidy toward electricity would be no longer needed because the total unsubsidized bill of end users would be lower than their current subsidised bill. This raises a start point for the government to discontinue energy subsidization to enhance a sustainable future.

The research recommends the application of the three proposed sustainable solutions (rammed earth, sustainable thermal insulation and solar PVs) through the establishment of a green building codes and regulations. The use of local materials (earth) and the abundance of sunlight almost all around the year are essential for the future of sustainability in Saudi Arabia.

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List of Abbreviations

Abbreviation	*Description*
A/E	Architectural/Engineering
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
BOS	Balance of System
BREEAM	Building Research Establishment Environmental Assessment Methodology
CASBEE	Comprehensive Assessment System for Built Environment Efficiency in Japan
CM	Construction Management
CMS	Chain Mountains of Sarwat
CPM	Critical Path Method
DCMM	Development Commission of Mecca & Mashaaer
DGNB	German Sustainable Building Council
ECTS	European Credit Transfer and Accumulation System
EPRS	Estidama Pearl Rating System
ECOSE	New Sustainable Binder Technology
ESEER	The European Seasonal Energy Efficiency Ratio
GACA	General Authority for Civil Aviation
GBCSA	Green Building Council of South Africa
GBIG	Green Building Information Gateway
GCC	Gulf Cooperation Council
GDP	Gross Domestic Product
GWe	Gigawatt Electrical

HVAC	Heating, Ventilating, and Air Conditioning
ICC	International Construction Code
IgCC	International Green Construction Code
IES-VE	Integrated Environmental Solutions Virtual Environment
JOD	Jabal Omar Development
JODC	Jabal Omar Development Company
KAEC	King Abdullah Economic City
KAMCM	King Abdullah Medical City in Mecca
KAUST	King Abdullah University of Science and Technology
KICP	KAUST Industry Collaboration Program
LEED	Leadership in Energy & Environmental Design
MEED	Middle East Economic Digest
MENA	Middle East and North Africa
MPTP	Mecca Public Transport Programme
PERT	Project Evaluation and Review Technique
QSAS	Qatar Sustainability Assessment System
SAMA	Saudi Arabian Monetary Agency
SEC	Saudi Electricity Company
SEER	Seasonal Energy Efficiency Ratio
SGBC	Saudi Green Building Council
SGBF	Saudi Green Building Forum
SSEER	System Seasonal Energy Efficiency Ratio
UNESCO	United Nations Educational, Scientific and Cultural Organization
WCED	World Commission on Environment and Development
WSSD	World Summit on Sustainable Development
WGBC	World Green Building Council

Chapter One: Introduction and Literature Review

1.1. Introduction

Saudi Arabia is a country located in the Arabian Peninsula and plays an important role in the Middle East and Gulf Cooperation Council (GCC). Globally, it is known as one of the leading countries in oil production. The total area of Saudi Arabia is 2,149,690 square kilometres (World Factbook, 2014). The capital city is Riyadh and the major cities are Mecca, Jeddah and Dammam. The history of the area goes back to thousands of years ago. Figures 1.1 and 1.2 show the maps of the Kingdom of Saudi Arabia with the 13 provinces with major cities and topography.

Figure 1. 1: Saudi Arabia's Map with Provinces and Major cities

(www.emapsworld.com, 2014)

Saudi Arabia's building systems have undergone substantial change in the last few decades. Prior to the oil revolution, constructions mainly consisted of solid, load-bearing walls made of mud or stones with roofs of wooden beams. Regional and climatic

patterns were evident as building in each region considered the climate and used local materials and local building skills.

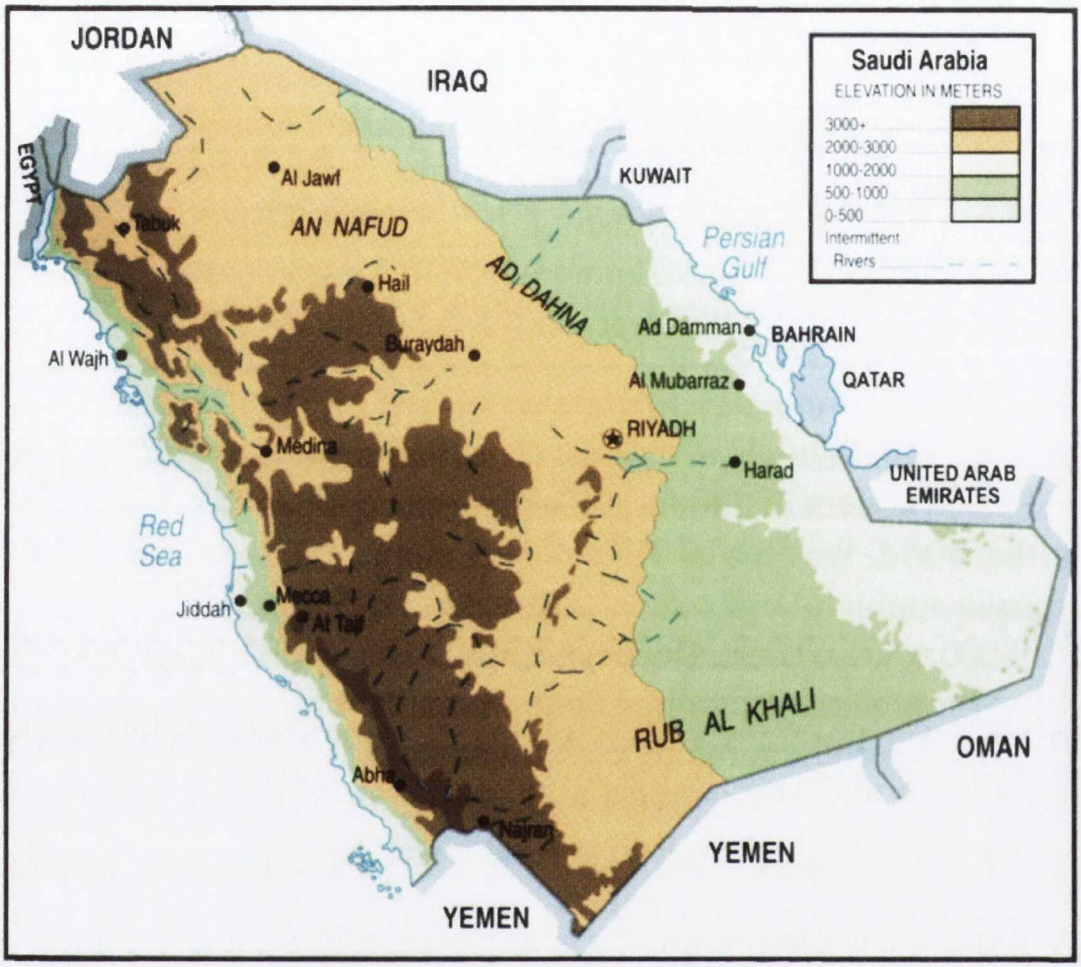


Figure 1 . 2: Saudi Topography Map showing Sarawat Mountains Chain in the West, Jeddah (Jiddah), Taif (At Taif), and Mecca.

(www.globalsecurity.org, 2014)

Sustainable construction has not yet been especially considered in this area. Saudi Arabia has the potential to increase environmental techniques and green construction practices especially in major cities like Mecca. The research will expand knowledge on sustainable construction specifically for this part of the world. One of the research aims is to reintroduce former practices of using sustainable materials in modern building and proposing suitable techniques and best practices.

1.2. Aims and Objectives of the Research

1.2.1. Research Aims

This research aims at enhancing and promoting sustainability in the Saudi construction sector through understanding the current knowledge, regulations and guidelines and modelling the application of appropriate sustainable building materials and techniques.

1.2.2. Research Objectives

The objectives of this research are as follows:

- To study and analyse existing current sustainable construction with respect to management, regulations, techniques and materials by means of questionnaires, personal interviews and background research.
- To determine sustainable techniques appropriate to Saudi Arabia.
- To determine the potential impact of photovoltaic panels (PVs), rammed earth, and building sustainable thermal insulation in Saudi Arabian construction through modelling.
- To propose and recommend sustainable construction practices for future consideration.
- To draw the attention of the government to the importance of sustainability in construction and encourage more sustainable legislation.

1.2.3. Research Significance and Contribution

The growth and development of human civilization has an impact on the natural environment. The life cycle of the buildings in which we live and work are responsible for the consumption of many of our natural resources that are needed to sustain the future life on our planet.

According to Garrigan (2011), 30 to 40 % of energy consumption and related greenhouse gas emissions are caused by construction and construction-related activities.

In addition, buildings are responsible for one third of resources use and about 30% of solid waste generation worldwide (Garrigan, 2011). For instance, about 50% of the United Kingdom's carbon emissions came from the energy consumed by building-related activities in 2006 (Walsh, 2016). Construction has impact on air quality, climate change gases, drinking water pollution, and landfill waste. Other studies indicated that buildings could cause some health risks due to indoor air pollution.

In the United States, buildings account for about 39% of total energy use, 68% for total electricity consumption, 30% of landfill waste, 38% of carbon dioxide emissions and 12% of total water consumption (Western North Carolina Green Building Council, 2016).

Around 90% of new construction will take place in developing countries (Garrigan, 2011). Saudi Arabia has the largest construction market in the Middle East. This gives an indicator of the urgent need to consider sustainable construction principles in Saudi Arabia.

There is a need for new green construction laws and regulations considering sustainable construction in Saudi Arabia especially in Mecca where the greatest amount of construction in Saudi Arabia (approximately 37%) is taking place. Although there are some sustainable buildings in the country, they were built by individual clients or companies with no national green building standards or regulations with regard to sustainable construction. This research intends to seek and propose appropriate sustainable construction practices that can be standardized or widely applied to a significant amount of buildings in the future to help achieve sustainability in Saudi Arabian construction.

Sustainable guidelines and regulations are absent in the country due to the lack of awareness among decision makers. In addition, these types of standards require more studies and expertise to gather and standardize the local needs, in which, are not readily available. Another factor could be the lack of sustainable materials and crafts markets. However, the drivers for change include the rise of awareness among all stakeholders especially the national standards authorities, the attraction of experts in this regard and the rise of studies and initiatives regarding sustainability and its advantages socially, economically and environmentally.

Historically, construction methods and materials were local and sustainable. However, after the oil boom in Saudi Arabia, the building industry became dependent on concrete and other materials of higher environmental impact. Thus, the research also intends to make better use of local resources to sustain the environment.

In contribution to knowledge, this research adds to the literature in a place where sustainability in construction is very limited or lacked to sustainability studies. In addition, the sustainable elements found in the research contribute in filling the gap of current lack of sustainable innovation in Saudi Arabia and similar conditions. The research provides solutions to current construction practices that were in need for more studies in Saudi Arabia. The research also widens the sustainability knowledge among stakeholders and decision makers by demonstration of new sustainable methods and their suitability to this specific region of the world. Findings base the foundation for further studies in this regard and laws and regulations could take advantage of this knowledge in many ways.

1.3. Ancient Constructions in the Arabian Peninsula

Construction types have evolved in response to problems and societal changes. Climate has also historically determined buildings in Saudi Arabia. Below are included some of the most significant historic and traditional constructions in the Saudi Arabia.

1.3.1. The Ka'aba

The Ka'aba is the direction for all the Muslims to pray across the globe. It is located in the centre of the Holy Mosque in Mecca, Hejaz Province in Saudi Arabia (Al Madenah and Makkah Provinces in Figure 1.1). According to most scholars, Prophet Ibrahim and his son Prophet Ismail were ordered by Allah to be the first to build the Ka'aba many centuries ago.

The Ka'aba is a square building made of stones, about 60 feet long, 60 feet wide and 60 feet high. Sanctity and antiquity of the Ka'aba is older than history itself as Muslims believe. The Ka'aba over this long period of time has gone through some renovations and in some cases needed to be rebuilt like when it was damaged by floods centuries ago.

"And [mention, O Muhammad], when We designated for Abraham the site of the House, [saying], "Do not associate anything with Me and purify My House for those who perform Tawaf and those who stand [in prayer] and those who bow and prostrate." (Qur'an 22:26)

"And [mention] when Abraham was raising the foundations of the House and [with him] Ishmael, [saying], "Our Lord, accept [this] from us. Indeed You are the Hearing, the Knowing."(Qur'an 2:127)

The building has been built with local stones. The building is a great example that stands for centuries. The local stones showed a great potential in terms of durability and applicability as more properties details are shown in Table 1.2. This example

emphasizes the fact that construction with local materials can stand for centuries and should be incorporated in future consideration of sustainability. Many other local materials will show up through the thesis.

1.3.2. Historical Madain Saleh

Madain Saleh is a UNESCO world heritage site (Figures 1.3 and 1.4). It is a pre-Islamic archaeological site dating from the Nabatean kingdom (1st century AD). Historic evidence places here the settlement of the Thamud people, after Noah and before Moses. It includes well-preserved remains from late antiquity, especially the 131 rock-cut monumental tombs, with their elaborately ornamented façades, of the Nabatean kingdom (Figure 1.4) and evidence of later cultures such as Roman. The Kingdom of Nabataean with its capital Petra, Jordan, expanded to dominate Madain Saleh, which reached the peak of civilization at that time. The settlers were an advanced culture, evidenced by practices such as the sophisticated carvings, drilled wells and rainwater tanks excavated in the bedrock. According to the World Heritage Centre (2007), the main construction material for houses, boundary walls and other structures were sun-dried mud brick; a material which was used in the area until the beginning of the oil boom in the last century. Table 1.2 shows the physical properties of earth and other main local materials used in the past putting forward the application of these materials in new sustainable constructions.

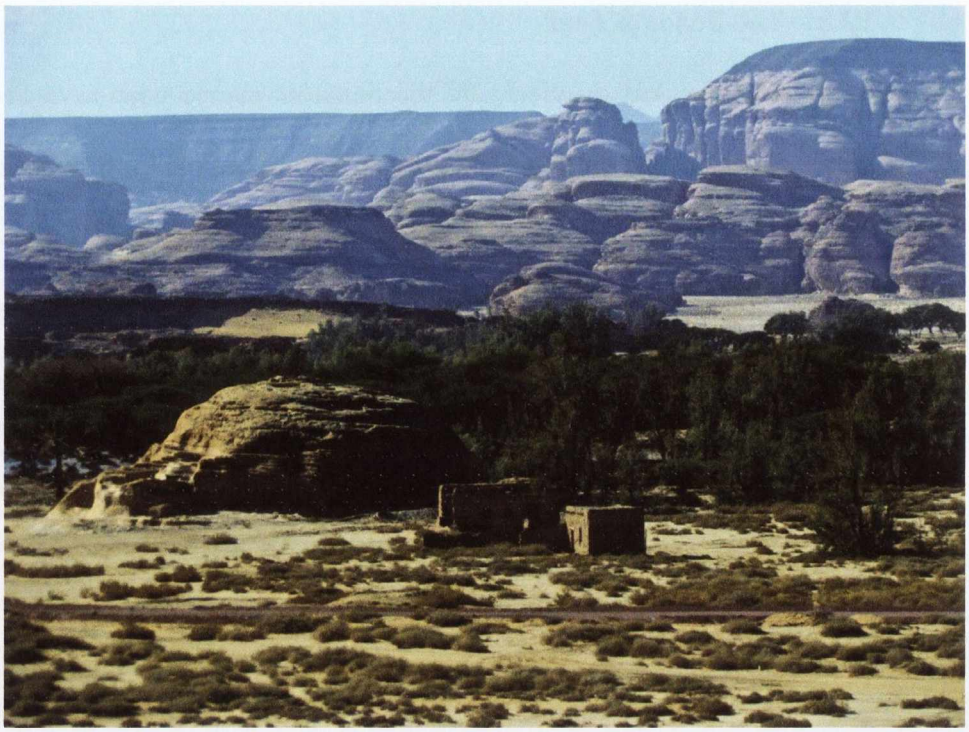


Figure 1 . 3: Madain Saleh View

(saudi-archaeology.com, 2014)

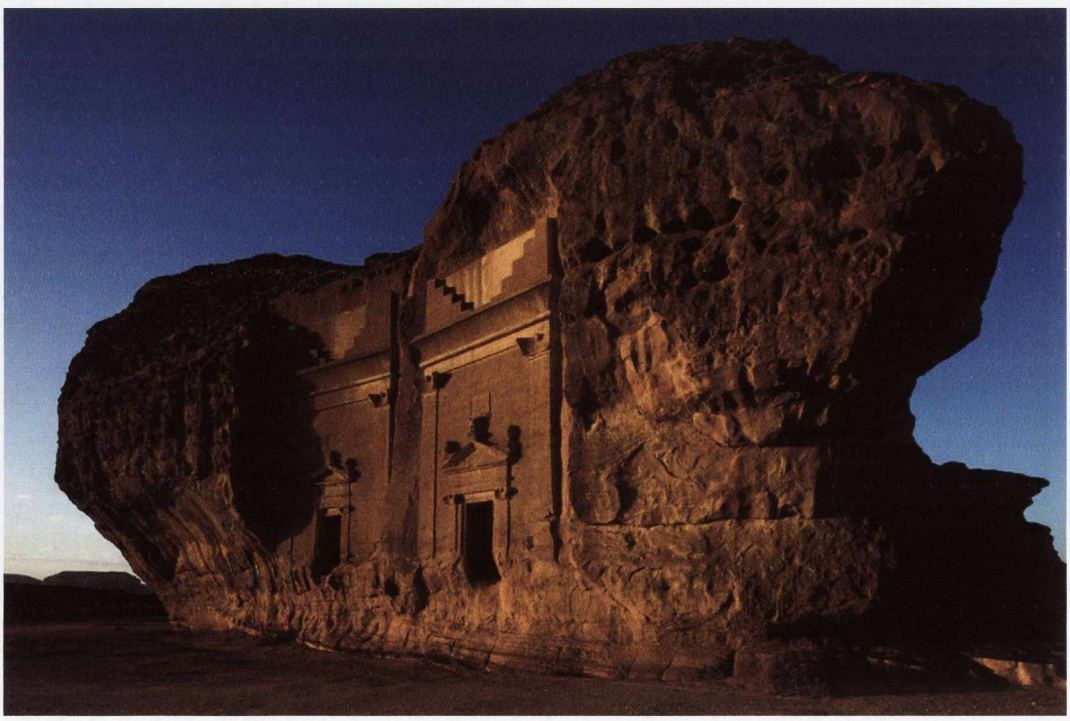


Figure 1 . 4: A View from Madain Saleh

(saudi-archaeology.com, 2014)

1.3.3. The Bedouin Tent

The Bedouins, desert dwellers, are the nomadic people who have been living in the Arabian Peninsula for around 1500 years. They use a simple lifestyle that includes tents as a nomadic shelter and the camel as means of transportation. Some basic necessities of life for desert dwellers are the camels, herds of goats and the black tent.

Trading, mobility and devotion to family and tribe have reflections on the pattern of settlements in the area. Tents were the way of shelter that is possible due to the nomadic way of life that requires Bedouins to travel and look for a climatically suitable place throughout the year. The nomadic way of life requires that the tent must be flexible, light and easy to be carried and erected.

As a start point in construction of the Arabian tent, Bedouin women are responsible to weave the tent's awnings from goats' hair or in some cases from camel hair, wool, or cotton. The width of a tent is varying from 7 meters to 45 meters, depending on the desired size of the tent (Talib, 1984). Children may join to erect poles and stretch ropes to the stakes while adults do the heavier jobs.

Three longitudinal rows of wooden poles are used to support the woven goat-hair that covers the Arabian tent. The front and back rows are kept lower than the middle row. Some nomads' tents use only two rows of wooden poles that are placed in the front and centre of the tent. In addition, anchor ropes are attached to the stakes in order to support and stretch the rear awning. In some cases, fewer supports may be preferred in order to reduce weight while traveling and also to save time during erection and dismantling.

Correspondingly, there is a stake to provide tensile strength to each row of poles. However, some of typical central Arabian tribes' tents have three rows of three poles each. Moreover, hemp ropes and wooden pins are used as fastenings. Also, additional covering may be used sometimes from thick woollen cloths. In general, tents are divided

into two sections. One of the sections is made for men while the other for women and the separation cloth is made of the same materials that are used for enclosures, walls. However, in the internal layout of the tent, women's section is larger than men's due to the need of more space for cooking, storage, and if there is a new-born baby in the family. Figures 1.5 - 1.7 show the described features of the Arabian tent in more detail.

The Bedouin tents are beautifully lit inside and when the outside of the tent gets hot, it causes an updraught that sucks air through the loose weave. Even though there is no breeze, the air comes screaming in when opening the tent flaps. However, when it comes to rain, the goat fibres swell up and the tent gets tighter. This provides a demonstration on how tents react to local weather. In fact, tents can be considered as a sustainable shelter that uses local natural materials with no emission production or any other harm to the environment.

Figure 1 . 5: Tent In The Desert

(wordpress.com, 2014)

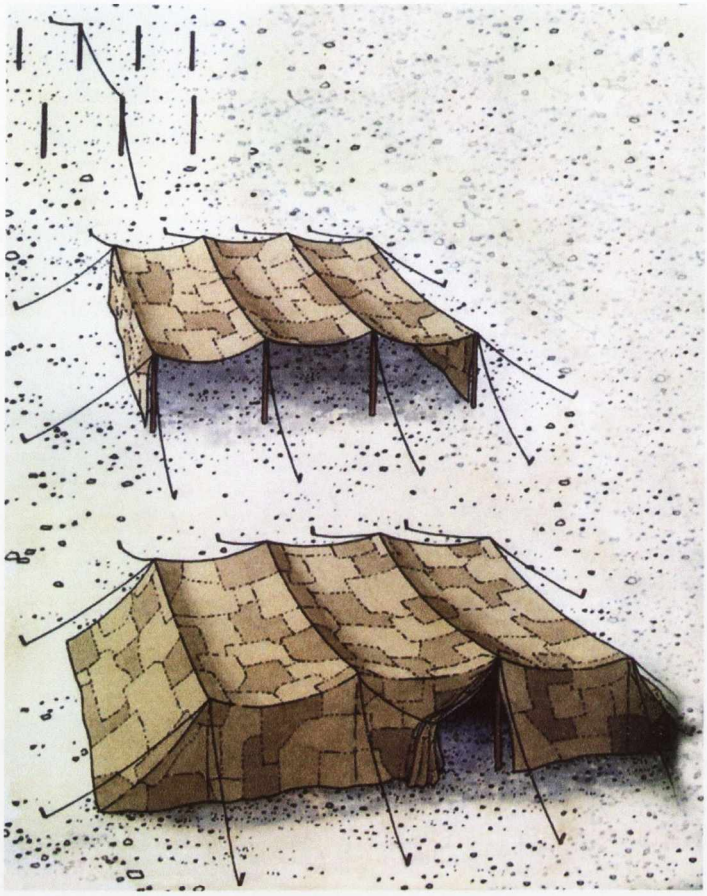


Figure 1 . 6: Process of Erecting the Tent

(byui.edu, 2014)

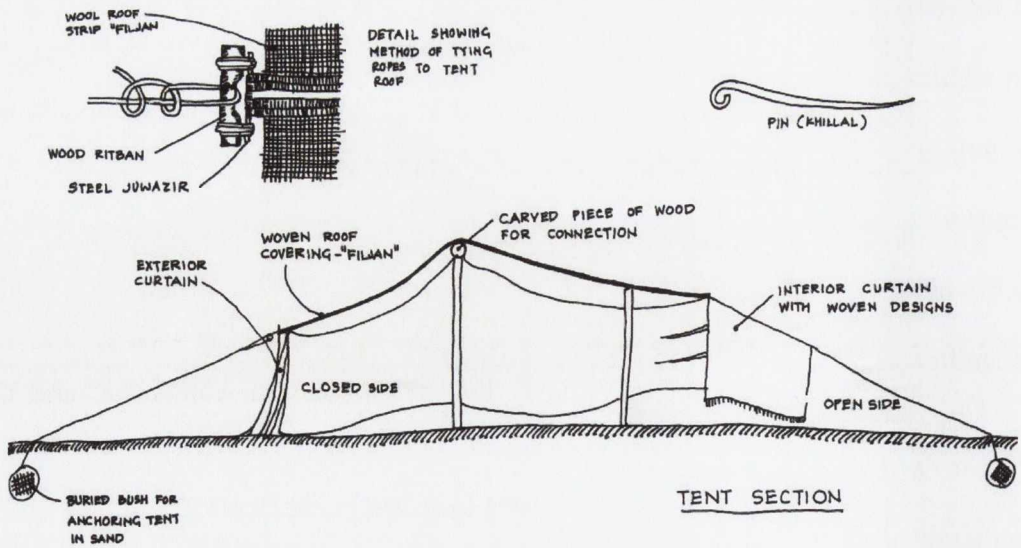


Figure 1 . 7: Tent Section

(Talib, 1984)

Tents were the example of historic way of life in this part of the world. This is to show how ancient people's life looks like. Bedouins were moving from one place to another to seek suitable climate for them and their animals since there were no permanent dwellings that effectively protect them from the harsh weather. People were seeking solutions to the way that they depended on tents for many years. Therefore, new construction types had been developed as builders experience new problems over the years. At that time, new types of buildings were established based on each climate condition throughout the area. These new constructions in the history started to change the way of dwellings that many people have had. The next section describes these in more detail as some of these old techniques and materials would eventually lead to a sustainable future as demonstrated later in chapter 7.

1.4. Historic Buildings in Saudi Arabia's Climatic Regions

Saudi Arabia has a harsh, dry desert climate with great temperature extremes. The nature of the climate was historically considered in construction and, as a result, historic buildings are based on climatic zones. Most traditional and historic buildings in the country were typically houses, souks (markets) or religious buildings (mosques). This section will consider features of the main traditional dwellings in Saudi Arabia, and how the resultant building is partially determined by the macro and micro climatic conditions around it. Most existing traditional buildings in Saudi Arabia are approximately 200 to 300 years old, however, occasionally 2,000 years old buildings can be found such as the Mosque in Tamania, Asir, south of Saudi Arabia. Kaizer Talib (1984), divided Saudi Arabia in four climatic regions: hot-dry, hot-humid, composite, and upland region (Figure 1.8).

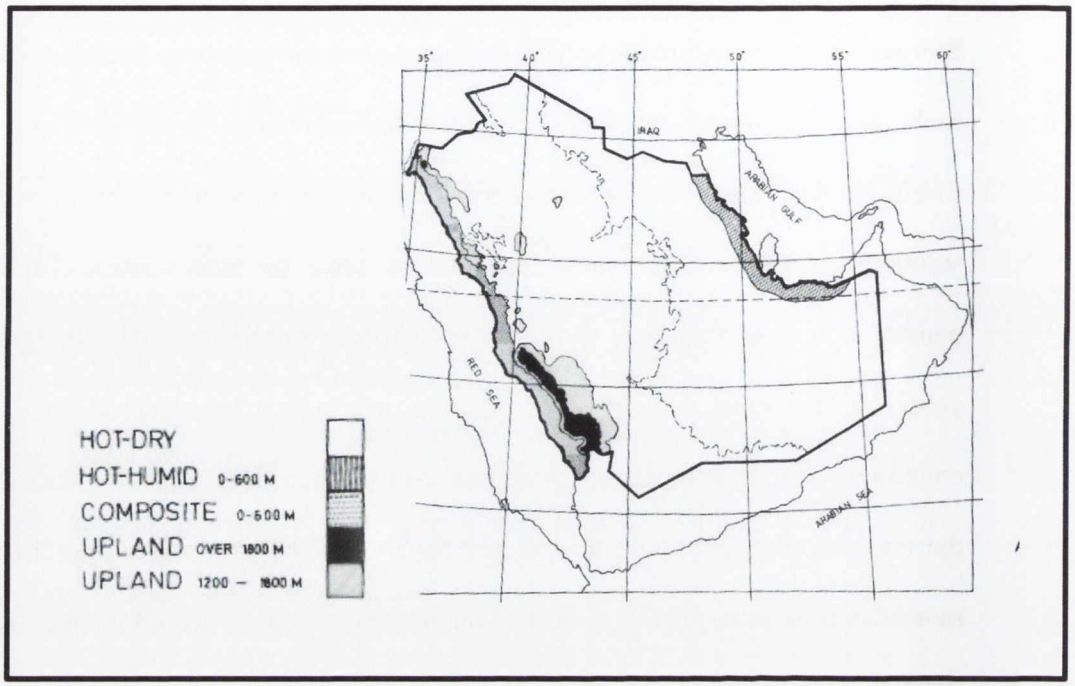


Figure 1 . 8: Map of climatic zones in Saudi Arabia

(Talib, 1984)

1.4.1. Construction in the Hot-Dry Region

This climate has a characteristic of inefficient precipitation. However, the Atrium Adobe Houses are the typical traditional buildings in this region. The core of the house is the atrium, which not only acts as a climatic moderator but it also provides privacy and constitutes a unique cultural feature of spatial significance. As a climate moderator, the Atrium House acts as an airshaft as well as a lightwell bringing both air-movement and day light into the rooms around it. In the summer, when the average temperature is around 43° C, the atrium and local earth materials decrease the temperature between 10 and 20° C. An old saying state that the Arab house was never complete, growing around a single courtyard over time or sometimes as a group of courtyard houses linked together. Construction materials, methods and techniques are distinctive in this region of Saudi Arabia. Table 1.1 shows more details on how builders traditionally and

historically responded to the hot dry climate. The table also summarises the outputs of these construction elements, which are often associated to an enhanced sustainability.

Building Element	Description	Output
Atrium	Acts as a climatic moderator and as a generator of a unique private lifestyle of culture and spatial significance Acts as an airshaft as well as a lightwell bringing both air-movement and day light to rooms around it	Air movement Cultural responsive design Daylight Privacy Reduced temperature
Growing Home or Never Completed House	A house that is never complete when built It grows around a single courtyard over a period of time and adding more rooms as needed Sometimes it is built as a group of courtyard houses that are linked together	Consideration of future extensions and changes Avoidance of waste and material resource Constructing while the building in use with no harm to occupants
Uncut Timber Beams	Timber members in the roof are left uncut and extended through the wall to the outside It could be connected to new beams to add a new room adjacent to the old one	Formation of a continuous structure
Close-knit Building Layout	Aligning buildings close to each other to generate mutual shading	Provides passive cooling from mutual shading Reducing heat gain on external walls
Green Space Areas	Filling the area around building with local plants of low water consumption	Protecting buildings from the sun Reducing heat gain on external walls, thus the indoor environment
Building Orientation	Longer dimensions of buildings are facing north and south in order to achieve the best solar orientation	Providing protection from glare, dust and wind
Limited External Openings and Windows	There are only few openings in the external walls of the traditional Arabian houses. The reason behind that is the existence of the courtyards in which most of fresh air and daylight are derived from it. Most doors and windows open around the courtyard at the same time under the protection of a colonnaded passage that is around the courtyard.	Openings are placed in well-protected location to provide privacy as well as to avoid glare. Small openings at higher level in the walls are used allowing light to go inside where the view is not desirable
Thick Walls	Traditional buildings in the area used thick walls that range between 45 cm to 75 cm. The walls are generally made of stone rubble or coral stone with mud or gypsum as the bonding material.	These intentioned thick walls insulate the building from the extreme solar heat and provide thermal balance. Thick walls work as a support for the ceiling. Ability to add one more floor

Thick Roofs	As the major source of heat gain mostly in the low-rise developments in the region, the traditional roofs were thickly built and sometimes similar to the walls thickness. Construction of roofs is made of stone rubble and earth supported on timber beams or palm tree trunks	Providing protections to the indoor environment from heat Preventing leaking and collapsing during heavy rains due to its thickness, which requires great amount of maintenance as well as the need of being built properly
Finishes and Exterior Light Colours	Buildings must be waterproofed and protected against flash rains. Smooth finishes will reflect most of solar radiation using light colours paints. Reflective external surfaces are more desirable than rough ones. In order to provide reflective external surfaces, whitewash is the cheapest, simplest, and most effective way of finishing although it must be done often. In traditional buildings the builders use gypsum and coral plaster. However, in regions where winter conditions require heating, northern region, some surfaces may be painted dark colours.	Reflective external surfaces and light colours reflect most of solar radiation, thus reducing the heat gains on external surfaces.

Table 1 . 1: Past construction methods and techniques used in the Hot-Dry Region (Talib, 1984)

1.4.2. Construction in the Hot-Humid Region

This zone is located mainly in the West coast along the Red Sea, which is extremely humid throughout the year. The narrow belt of 12 to 15 km along the coast is influenced by the proximity of a large body of water. In addition, composite climate characteristics may be observed beyond this humid belt due to the adjacent hot-dry climate.

In Hejaz, the Western Province of Saudi Arabia, the vernacular architecture evolved into refined building arts and technologies. The city of Jeddah, a trading port and the second largest city in the country, played a prominent role due to the cross-cultural trading between Middle East, Asia and Europe. Moreover, pilgrims who came from various parts of the world brought their skills and ideas. A better use of materials and a superior technology in Hejaz constructions resulted from the mixing of different cultures and different technological skills. For instance, *Rowshans* and *Mashrabiyas* (projecting screened windows), which are nowadays considered as historical prominent features in the Hejaz actually came from Egypt. The main function for a rowshan or mashrabiya was to provide cross-ventilation while providing privacy for residents and sometimes

functioning as a "secret eye". However, after some time and due to their popularity, rowshans became decorative in some areas. According to Talib (1984), the rowshan may be described as a projected bay-window with decorative wooden screens as enclosures. It is constructed entirely from cantilevered timber framework and usually installed over an opening after prefabrication. A further advantage of rowshans is to shield earthenware jars filled with water in order to provide evaporative cooling (in hot-dry regions like in Mecca and Medina) and cool water. A mashrabiya is a complete assembly of rowshans on a façade, one above the other as it may be described. Mashrabiyas may cover the whole façade in some of large houses of rich and important families. Figures 1.9 and 1.10 show details of these elements.

Figure 1 . 9: Different types of Mashrabiya in historical city of Jeddah

(Alitany et al. 2013)

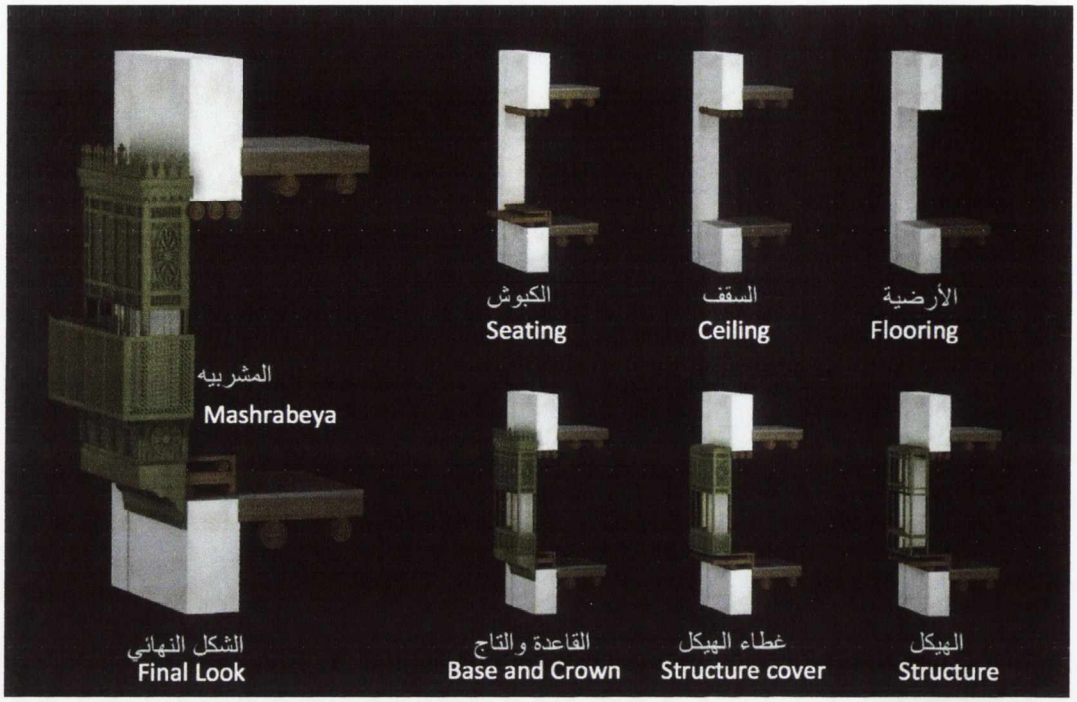


Figure 1 . 10: Process of the Rowshan/Mashrabiya's construction

(Hazmi et al. 2007)

The vernacular architecture of Saudi Arabia responds to the hot-humid climate using following techniques:

- *"Construction of tall, airy structures which allow cross-ventilation;*
- *Placement of rowshans on facades;*
- *Construction of skeletal structure of heavy columns which allows the building to be light and airy;*
- *The use of coral or gypsum as a bonding material and a sealant in stone construction. Gypsum is also used as plaster.*
- *The use of internal plans which provide each room with cross-ventilation through external façades;*
- *The use of internal plans which place bedrooms and family rooms on upper floors to take advantage of on-shore and off-shore breeze;*
- *Construction of buildings apart from each other, where possible, to allow free movement of air around the building.*
- *In congested areas of Jeddah, building façades project as many rowshans as possible.*
- *Wider streets allow passages of air except in the densely built, poorer sections."*

The main building material reflecting the agrarian economy is adobe, unburned sun-dried brick, mixed with materials derived from the palm tree. However, the rich merchants in Jeddah used coral stones mined from the Red Sea as building stones as well as expensive wood craft from India, North Africa, East Africa and Southern Europe. In the south of the hot-humid region (Jizan and Najran areas) conical huts were built from dried river reeds with mud-plastered walls and roofs (wattle and daub technique). These, originally African and became the form of construction in this region from settlers from Sudan and Ethiopia who arrived centuries ago. This type of construction prevents the accumulation of heat, a priority in this climate. Although there are no openings except the doors, the mud and reeds provide continuous air change. Thus, these huts provide comfortable conditions similar to tree shading. The semi-open construction of the roofs allows hot air and smoke to escape from the interior while the reeds on the outside provide a protective shield for the internal mud plastered dome roof. Therefore, it creates a protective shadow while providing sufficient air-change.

Although the construction practices above have valuable sustainable characteristics, they may not be practical for modern residential building. However, the integration of some of these methods and materials may be appropriate and efficient to enhance sustainability in modern construction.

1.4.3. Construction in the Composite Climate Region

There are great challenges for building designers in the composite climate region due to the fluctuation of conditions between hot-dry, hot-humid and maritime desert conditions in various locations. According to Talib (1984), in Dhahran, Eastern Province on the Arabian Gulf, the climate is characterized by the harshness of July and August temperatures of 42° C average (with lower humidity) and pleasant months of December and January when temperatures average 22° C (with more humidity). The Qatif city area, Eastern Province, has responded well to the climate, culture and material conditions of

the farming community. The adobe mud house is the typical traditional construction in this region including elements like the courtyards, thick mud walls, openings onto courtyards, wood-framed mud roof and floor construction and small external windows.

The courtyard is a private open space surrounded by walls and acts as climate moderator. This provides a better indoor environment for residents. However, the use of thick mud walls acts as load bearing walls as well as a thick thermal insulation. The use of local earthen materials is a great way of building sustainable construction in the past as well as the future. Other elements were used in the composite climate includes the use of opening onto courtyards in which they had been used for privacy reasons as well as for sun glare avoidance.

1.4.4. Construction in the Upland climate Region

This type of climate is mainly found in the upland of the Asir Province near Yemen. This has influenced the construction design and methods and provided a tower-like character similar to Yemen's architecture. Villages are spread along wadis, sometimes including only four or five houses. Large villages are built on top of hills while farms are built on the lower slopes. Houses are tall, three to four-story fortress with small openings that could be closed by wooden shutters and used sometimes for shooting at the enemies. They form narrow alleyways being built close to each other. The response to climate has led to tall, handsome tower-like structures, often tapering towards the top buildings. In fact, there are four types of tower houses of this area based on the materials used: mud tower-houses; stone rubble tower houses; stone apron tower-houses (with mud structures above the ground floor- referred as Abha style) and mud/slate tower-houses.

Mud Tower-Houses:

Agrarian communities used adobe and rammed earth to build mud towers. Madamek, layers of earth 30 to 40 centimetres high were laid (one layer per day) using communal labour, making a simple structure that is usually tapering upwards. A layer of madamek was allowed 24-to 48-hours to dry after which the second layer was laid. Rammed earth was used on the ground floors. Small openings appear in each floor, gypsum plastered is cheerfully painted. The thick walls in these houses have high thermal mass, therefore, they can store heat during the day and release it overnight when temperatures drop. Windows are kept closed during winter to avoid cold winds. However, in the summer, through-ventilation of rooms keeps the building pleasantly cool. Balcony-like terraces and rooms built in the roofs are the preferable places to sleep during the humid summer time.

Stone Rubble Tower-Houses:

A high percentage of houses in the Asir mountainous region are built from stones gathered from nearby hills. In most cases, they consist of dry walls built without mortar and with small stones are inserted between large rubble stones. This is called dry rubble masonry. They are usually one or two storey high. On the ground floor, walls may be as thick as 70 centimetres. The openings in rubble houses are small. Exposed structural timber members are also used.

In current constructions, masonry walls comprise one of the major energy consuming components of the building. This is greatly seen in case of load bearing masonry structures (Venkatarama et al, 2003). However, advantages of using stone masonry are varied. In fact, they are local, strong, durable, and fire resistance. In addition, stone can be a superior insulator as they actually help keeping indoor comfort; they slowly heat

during the day, and then radiate warmth through more of cool at night (Sharon and Watson, 1981).

Abha Style Tower Houses:

These buildings were built with rubble stones as well as sun-dried mud. Either the whole or parts of the ground floor, load-bearing walls are built of rubble stones. Using local adobe building techniques, the upper walls are built of sun-dried mud (madamek in Arabic). The upper floors are usually used for living while the ground floor is used for storage. This construction method is widely used in the city of Abha, the capital of the Asir Province.

Mud and Slate Houses:

It drizzles or rains most of the year in Asir. As a result, mud walls need constant maintenance to avoid damage and erosion by rain. As protection, slate (an impermeable, metamorphosed mudrock) is inserted into the mud walls. This requires elaborate skill. In fact, prosperous farmers who do not favour the ordinary mud-tower houses prefer this type of building. Generally they are three to five-stories high and similar to mud-tower houses, however, external maintenance is minimal. This is a valuable construction technique that uses local materials with no harm to the environment. This as an example of an old method is nowadays ignored, in which, this can advance sustainability in construction of this region.

1.5. Summary of Old Building Materials in Saudi Arabia

Materials used by old builders were various as discussed above. Most of these materials were sustainable and produced locally. Table 1.2 includes the properties, use, environmental advantages and disadvantages of these materials.

Material	Physical Properties	Use	Environmental Advantages	Environmental Disadvantages
Clay / Adobe	Easy to use Extremely durable in arid climate High heat capacity High thermal mass Strong in compression Weak in tension and shear	Production of bricks Production of roofing tiles Clay, water and an organic substance such as dung or straw. The major soil components are sand and clay, with straw being used to bind. The straw is also important for even drying of the brick to prevent cracking Used in construction of walls. Placing of adobe bricks in courses, with each course being laid on the entire length of the wall. THIS Used in roof construction. A mixture of organic materials, sand, water and clay was formed before its pressing into wood forms was done. This produced earth-brick rows which were laid across a supporting structure	Renewable source Biodegradable Easy to clean as it is water soluble Inexpensive Locally available Low embodied energy No CO_2 emissions resulting from manufacture No toxins, no chemicals released on manufacturing Non-toxic Obtained through natural means with little energy requirement Reusable Regulates internal moisture	Damaged by earthquake like in Chile earthquake in 2010 and Bam earthquake in 2003.
Lime	Anti-bacterial Durable Ultra-violet resistant Water-vapour permeable Mechanical strength and durability subject to hydraulic strength	External renders In lime plasters and mortars Internal plasters Masonry wall infill Pointing and bedding masonry mortars	Absorbs atmospheric carbon dioxide Biodegradable Can be produced in small scale. Has a gentle binding property for full re-use of other elements. Locally available in Saudi Arabia (Hydraulic lime) Local natural material No Chemicals Very Strong	Green house gas emission High Embodied Energy High fossil fuel consumption
Rammed earth	Durable Easy to use High heat capacity High thermal mass Readily available Strong in compression	Construction of walls with wooden planks are used as a form. A spacer bolt is used to separate the planks. Earth is rammed into the form in layers. The filled form is removed, superimposed on the	Absorbs heat and releases it when temperature drops, reducing the energy requirement for heating and air conditioning. Associated with low manufacturing impacts Biodegradable	Failure to use mechanical tools may be time consuming, increasing the construction cost. Susceptible to water damage Needs maintenance in moist areas.

		top of the building's wall until the appropriate height is reached through additional ramming. The preferred soil should contain 70% sand and 30% clay to improve compressive strength. To increase weather resistance, walls were treated with bitumen, linseed oil or plaster.	Economically sustainable since the soil is readily available, cheap and requires unskilled labour. Fireproof Low embodied energy Non-toxic Reinforced earth prevents the negative effects of heavy storms Renewable Reusable Soundproof Termite-resistant	
Stone	Durable Great variation in physical properties depending on parent bedrock High thermal mass Strong	Used in building foundations Used in walls Used for flooring in some cases	Biodegradable Does not produce toxins Fire resistant Renewable Reusable	Quarrying activities impact the environment negatively Transport can increase cost and embodied energy
Thatch	Durable Easy to repair Flexible Light Withstands heavy rains and strong winds Breathable Impermeable in good condition	Roofing	Aesthetically appealing Available in some parts in Saudi Arabia Biodegradable Renewable	Flammable Labour intensive and requires skilled workers hence strains the economy Materials such as reeds are expensive May require chemical treatment
Timber	Light-weight, low density Good mechanical strength (strong for its light-weight) Easy to use Electricity and heat insulator	Building walls Flooring Roofing Wooden arts in buildings	Biodegradable Chemically inert Economically sustainable Low embodied energy Low toxicity Renewable	Causes soil pollution Difficulties in construction site control Flammable Leads to deforestation Not readily available in Saudi Arabia

Table 1 . 2: Historical building materials used in Saudi Arabia

Although some of the above materials have proven their performance with respect to climatic conditions, they are currently ignored by industry. Instead, materials like glass, concrete, and steel are widely used today. In addition, the use of natural ventilation and

passive design along with some of the materials used in the past can also enhance sustainability in construction.

In particular, earth materials have the potential to enhance sustainability in Saudi Arabia. Unlike other techniques and materials, they were widely used throughout the country despite the differences in climate. The hygro-thermal advantages of earthen materials will be discussed below (Chapter 3), however, they have proved they are climate responsive in the different regions of Saudi Arabia as discussed above. For example, they can lower indoor temperatures by 10-20° C when correctly designed (Talib, 1984). As a result of the recurrence of earth materials in the different climatic regions, their wide availability, hygrothermal properties and durability in the Saudi Arabian climate, these materials were chosen for further study and analysis (chapters 6 and 7).

However, technological advances of civilizations and the constructive techniques have been forgotten or displaced for some time in many countries like Saudi Arabia. These are now going through a revival process in some countries across the globe like USA and Europe. Traditional techniques are such as mud, lime and other earthen materials are now reconsidered, recovered and being updated in the construction sector as one of them is proposed for further investigation in this research later on. However, the concept of advancing and growing a home according to family needs is being used currently in some Latin American countries like Peru and Chile for example.

1.6. Construction Management

Construction management requires innovation, strategy, efficiency and a continuous effort for quality improvement. Optimising success in construction projects and management operations are inherent objectives of construction management. Researching trends in construction management can be used to enhance sustainable

construction. According to Badouri (2007), *"Oil-fuelled economic growth, coupled with favourable demographic fundamentals, growing commercial prominence and booming tourism, has led to an unprecedented construction boom in the Middle East, with the UAE and Saudi Arabia being the star performers. Other key catalysts include repatriation of investment funds from the US after the 9/11 incident, Governments' encouragement to private investment in the construction sector, as well as liberalisation of laws regulating foreign business activities and property ownership.*"

Clearly, there are significant opportunities for the development of construction. Managing construction projects amid growing environmental concerns have given rise to procedures that seek to be as harmless to the environment as possible. While green buildings have become increasingly popular; regulations relating to environmental damage and resource utilization have appeared in many nations.

Construction management can impact the environment if lacking sustainability principles. Understanding the environment leads to sustainable construction management. Some green construction companies use the impending environmental crisis as their selling point regardless of the validity of their arguments. In the construction industry, the environmental angle has developed to an extent that various certifications and standards concerning environmental impact must be incorporated with building operations. Companies may be certified to be compliant with a spectrum of environmental regulations or energy efficient areas, while project bids may be designed around environmental certification and building processes under the project management. Green construction includes energy efficient lighting, use of recycled material, reduced use of plastics and hazardous chemicals, efficient plumbing fixtures, recycling construction waste (or disposing of it in a more environmentally friendly manner); solar heating and solar electric fixtures, using local building materials, collecting and using rainwater, "eco roofs" which are topped with soil and local plants,

strategic utilization of natural light for energy efficiency (Alvin Inc., 2010). Meanwhile, it should be noted that certain sustainable projects are partly driven by informed and motivated customer requests.

1.7. Construction Industry Overview in Saudi Arabia

Nowadays, the construction industry face challenges due to the progressive amount of complex projects, project backlogs and limited new project engagements due to on-going economic uncertainty. As a result, the industry is experiencing increasing competition from existing and new diversifying competitors (KPMG International, 2014). However, construction output will grow to reach about $12.7 trillion and will account for 14.6% of world output by 2020 (Global Construction Perspectives Ltd. and Oxford Economics Ltd, 2013). However, according to Jones (2013), construction output is expected to increase to reach $15 trillion worldwide by 2025.

According to Tuknov (2013), the construction industry has obviously shaken and grown into renewed strength and vitality toward the close of the first decade of the 2000's after some economic shortages of stability. In fact, a period of continued recovery with new design innovations that helps in bringing more diverse construction landscape is predicted by most industry observers. From past years, the trend toward the sustainable construction is expected to continue with more constructions that embody green principles integrating natural elements in more inventive ways. The source above also stated that there are some expectations for a growing market demand for more eco-friendly options in terms of materials, construction and design. In addition, these developments involve a growing global awareness of the fundamental role that construction plays in helping preserve the environment. Construction may well become a key player in the on-going quest toward more green and sustainable industries in the world.

Saudi Arabia is the largest economy as well as the largest construction industry in the Middle East and it is expected to further grow in the coming years (Dajani, 2012). The construction sector across Saudi Arabia is considered to be the largest and most rapidly growing market in the entire Gulf Cooperation Council (GCC) region (U.S.-Saudi Arabian Business Council, 2010). The present projects across the GCC region are worth nearly $2 trillion USD, and approximately one third of all projects are located within Saudi Arabia. Ideal economic conditions, demographic factors, levels of governmental support, weather and geological factors have been found to contribute to the success in growth (U.S.-Saudi Arabian Business Council, 2010).

In fact, the Saudi Arabian construction market is valued at $732 billions according to Middle East Economic Digest (MEED) and MEED Projects Data, (2013). This number includes projects currently underway and those confirmed and in pre-execution stage. Nowadays, the construction market in Saudi Arabia is the most valuable market within the GCC region according to The Big 5, which is the largest construction exhibition company in the Middle East. According to Waugh (2013), examples of mega projects include the Riyadh Metro and King Abdulaziz International Airport.

The Saudi Arabian construction industry has increased significance for several years (White, 2013). Saudi companies are looking to highlight local market expertise and experience and increase market opportunities expanding business in the country. White, based on the current construction of six economic cities, transport, power and oil and gas facilities expects the increasing trend to continue.

Construct Arabia (2013), stated that, *"The Kingdom of Saudi Arabia's demographics are calling for an increase in construction spending. With an eye towards a sense of fiscal solvency separate from the energy sector and a young population eager for new*

real estate, all signs point upward with project capital expenditures projected to reach nearly 76 billion dollars in 2013."

In the coming years, the Saudi Arabian construction market is slated to undergo a dramatic revitalization. The sector is set to become the fastest growing in the Kingdom's economy by 2015 with a projected growth rate of 35% over the next three years (Construct Arabia, 2013). In addition, capital investments are increasing since the government is developing socio-economic infrastructure for the benefit of its citizens and future economic prospects. According to The Big 5 (2013), a stunning USD 76 billion of the national budget was allocated to the development of construction projects in the country in 2013 alone, and this figure is expected to exceed $3 trillion by 2020. Construct Arabia also indicated that the majority of these funds are directed towards mega projects, some of which are presently on going. These include six major economic cities (Table 1.3) with a budget over $160 billion. Other iconic projects include the $40 billion Sudair Industrial City, the $15 billion King Faisal University (KFU) and the $16 billion Jeddah Kingdom Tower that vies to unseat the world's tallest tower, Dubai's Burj Khalifa. Tables 1.4 to 1.7 show the major construction projects in Saudi Arabia.

The growing construction market in the country should include a major change in terms of sustainability. For example, a city look like Masder in the UAE is essential to prosper and inspire the nation. Other on-going and planned projects would have a great impact on the economy, the environment and the social aspects if were to include sustainable practices.

Economic City	King Abdullah Economic City (Rabigh)	Jizan Economic City (Jizan)	Prince Abdulaziz bin Musaed Economic City (Hail)	Knowledge Economic City (Madinah)	Tabuk Economic City (Tabuk)	Eastern Province Economic City
Area (sqkm)	168	103	156	4.8	135	n/a
Investment (US $Bn)	53	27	8	7	50	n/a
Jobs (mn)	1	.05	.055	.02	.4	n/a
Population (mn)	2	.25	.3	.15	1	n/a
Focus	Ports, logistics, light industry & services	Heavy industries, agro-industries, social development	Logistics, agribusines, minerals & construction material	Knowledge-based industries, tourism	Logistics, trade & Industry, environment	Energy, Resource
Scheduled Completion	2016	2011	2018	2014	n/a	n/a

Table 1 . 3: The Six New Economic Cities in Saudi Arabia

(U.S. - Saudi Arabian Business Council, 2014)

Project Name	Developer	Project Value (US$ million)	Status
Shams Al Arous	Dar Al Arkan	2,000	Ongoing
Housing Project 5,000 Villas	Saudi Binladin Group	1,400	Ongoing
Jeddah Housing Project	-	1,000	Ongoing
Al Mada Towers	-	600	Ongoing
Jubail Housing Complex	Azmeel Contracting & Const Company	235	Ongoing
SASREF - Housing Project	Khonaini International Company Ltd	100	Ongoing
Construction of 280 Villas located in Haii Al-Oyoun and Haii Al-Nakheel in Yanbu Industrial City	Asad Saeed Company for Contracting	73	Ongoing
Family Apartments in Jubail Industrial City	Al Kifah Construction Equipment Company	37	Ongoing
National Guards Villas	Saudi Oger Limited	-	Ongoing

Table 1 . 4: New Residential Development in Saudi Arabia

(ALPAN Capital, 2012)

Project Name	Developer	Project Value (US$ million)	Status
Bawwabat Al Sharq	Ansab General Contracting	400	Ongoing
King Abdullah Financial District - Capital Market Authority Tower	Saudi Binladen Group	300	Ongoing
Olaya Towers	Nesma Construction Co	235	Ongoing
Headquarters Business Park	Freyssinet Saudi Arabia Company Limited	214	Ongoing
Al Rajhi Bank (Headquarters Building)	-	200	Ongoing
King's Road Tower	Saqeifat Al Safa	133	Ongoing
Al Reziza Commercial Tower	-	100	Ongoing
Granada Business Park	GOSI	-	Ongoing
ITCC	The Rayadah Investment Company (RIC)	-	Ongoing
KAFD	RIC	-	Ongoing

Table 1 . 5: New Offices Development in Saudi Arabia

(ALPAN Capital, 2012)

Saudi Arabia Infrastructure: On-going Railway Projects		
Project Name	Project Value (USD)	Completion Date
SRO – Haramain High-Speed Rail (HHR)	29,100,000,000	1Q2017
SRO – Haramain High-Speed Rail (HHR) – Phase 1	21,100,000,000	Jan 2014
SRO – Haramain High-Speed Rail (HHR) – Phase 1 – Part 1	18,700,000,000	Jan 2014
SRO – Haramain High-Speed Rail (HHR) – Phase 2	8,000,000,000	1Q2017
PIF – Saudi Lanbridge	7,000,000,000	2015
SAR – North-South Railway	3,600,000,000	4Q2015
SRO – Haramain High-Speed Rail (HHR) – Phase 1 – Part 2	2,400,000,000	Jan 2014
SAR – North-South Railway Package 4	725,000,000	4Q2015
SAR – Jubail Railway	500,000,000	2016
SAR – King Khaled International Airport – Railway Station	187,000,000	2Q2015
SAR – Jubail Railway – Phase 1	177,000,000	2015
SRO – Al Ahsa Railway	93,460,000	2014

Table 1 . 6: Railway Projects in Saudi Arabia

(Kuwaiti Finance House Research Ltd., 2013)

Saudi Arabia Infrastructure: On-going Port Projects		
Project Name	Project Value (USD)	Completion Date
SAGIA – King Abdullah Economic City (KAEC) – Phase 1 – Sea Port	26,600,000,000	2020
MARAFIQ – Yanbu Industrial City – Marine Facilities	210,610,000	Aug 2013
Aramco – Dareen Port Expansion Project	35,000,000	1Q2014

Table 1 . 7: Port Projects in Saudi Arabia

(Kuwaiti Finance House Research Ltd., 2013)

There are a number of key factors that are driving this expansion including the need for the country to strengthen its internal infrastructure so as to diminish its reliance on the oil and gas sector and establish itself firmly as an industrial economy (The Big 5 Saudi Arabia, 2013). Another important factor is the rising demand for housing given the rapid increase in the local population (about 40% are under the age of 14). It is not surprising that the Saudi government is attracting much foreign interest in terms of investments and joint ventures with locally based firms in the construction sector considering the fact that the GDP is rising at a consistent rate of 7.5% per year (The Big 5 Saudi Arabia, 2013).

Other factors that drive the Saudi construction market progressive growth include the availability of vast amounts of undeveloped urban land, the steady growth in religious tourism (in Mecca and Medina), the impending implementation of the new mortgage

laws, the upcoming economic cities developments, and the growing population with increased per capita income (Bharat Book Bureau, 2010).

According to Construct Arabia, the knock-on effect of keynote investments has already started to extend across the construction industry, with real estate that is swiftly rising to become the Saudi's second largest economic sector after oil, expanding at a rate of 6% per year, with cement sales growing 12% in 2012. For the next coming years, major expenditure of approximately SR 65 billion (1 USD equals 3.75 Saudi Riyal), is also concentrated in transportation and infrastructure development, with plans for 3700 kilometres of roads as well as a national railway which is currently under construction, (The Big 5 Saudi Arabia, 2013). However, according to same source, challenges in Saudi construction nowadays remain in the form of time lags in the execution of legal procedures and regulatory adjustments, delays in construction projects and fluctuations in the market prices.

Clearly, both the strong financial position of the Saudi government and the political will to see these projects to fruition ensure that the market shall maintain its buoyancy in the long term. However, on the other side, the Saudi construction market still suffers a few pangs in the form of project delays, delays in execution of laws, conservative banking policies and lack of transparency.

Despite these disruptions, the amount of construction projects in Saudi Arabia has been increasing over recent years. These include government's mega projects such as the new 6 economic cities across the country, infrastructures, transportation, industrial, energy and residential complexes. Moreover, private constructions including domestic dwellings and commercial buildings are also expanding assisted by the country's economic growth. Table 1.8 shows macroeconomic data while Figures 1.11 and 1.12 show problematic factors in doing business in Saudi Arabia and the forecast of

construction growth in Saudi Arabia. Also Figure 1.13 illustrates the construction project value breakdown per sector in Saudi Arabia.

	2008 Actual	2009 Actual	2010 Actual	2011 Actual	2012 Estimate	2013 Forecast	2014 Forecast
GDP							
Nominal GDP (USD m)	5,522	4,367	5,268	6,695	7,497	7,557	7,901
Real GDP growth (%)	4.2	0.1	4.7	7.0*	5.7	4.1	4.9
Origin of GDP (% real change)							
Agriculture	0.7	-0.5	-1.0	2.2	-0.5	-0.3	-1.0
Industry	4.4	-3.4	4.7	8.2	6.6	3.5	4.8
Services	4.6	4.3	5.0	6.6	5.2	5.2	5.0
Population and income							
Population (m)	25.5	26.3	27.1*	28.0*	28.9	29.8	30.8
GDP per head (USD at PPP)	26,580	26,018	26,775*	28,361*	29,614	30,483	31,628
Fiscal indicators (% of GDP)							
Government revenue	53.2	31.1	37.5	43.9*	43.1	37.5	36.1
Government expenditure	25.1	36.4	33.1	32.0*	30.3	33.3	34.9
Government balance	28.1	-5.3	4.4	12.0*	12.7	4.3	1.2
Net public debt	16.1	19.3	14.1*	11.2*	11.1	11.9	10.6
Prices and financial indicators							
Consumer prices (av; %)	9.9	5.1	5.4	5.0	4.5	4.4	3.3
Deposit rate (av; %)	2.9	1.2	1.2*	1.2*	1.1	1.0	1.2

Table 1 . 8: Macroeconomic data of Saudi Arabia

(Deloitte & Touche M.E., 2013)

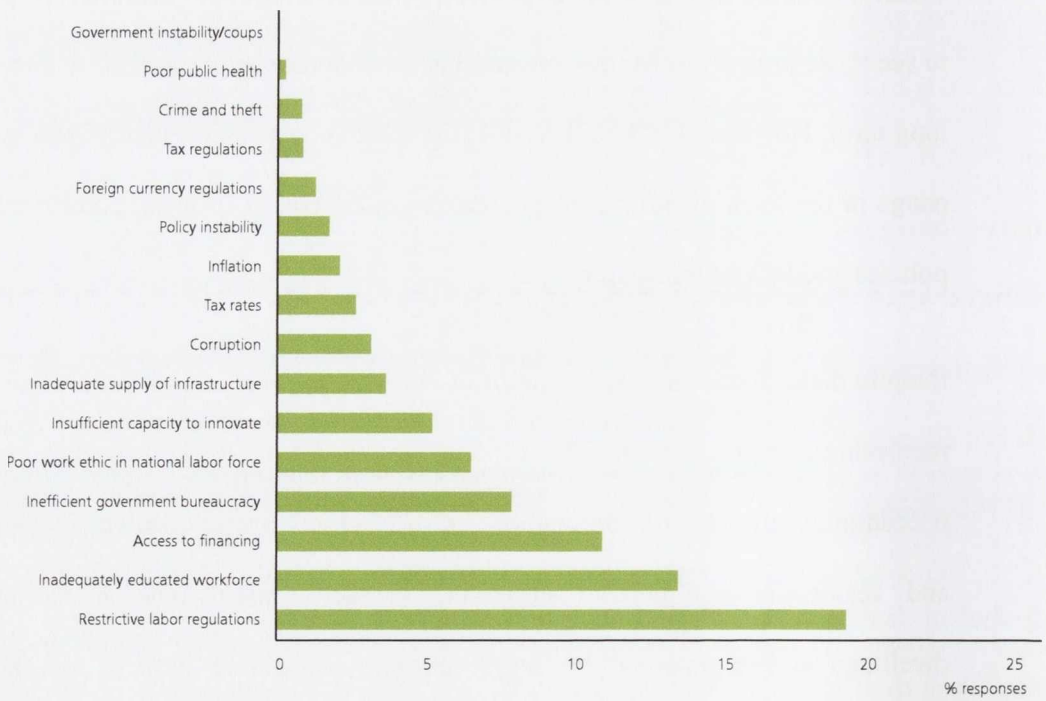


Figure 1 . 11: The problematic factors for doing business in Saudi Arabia

(Deloitte & Touche M.E., 2013)

Figure 1 . 12: The Estimated construction growth in Saudi Arabia

(Deloitte & Touche M.E., 2013)

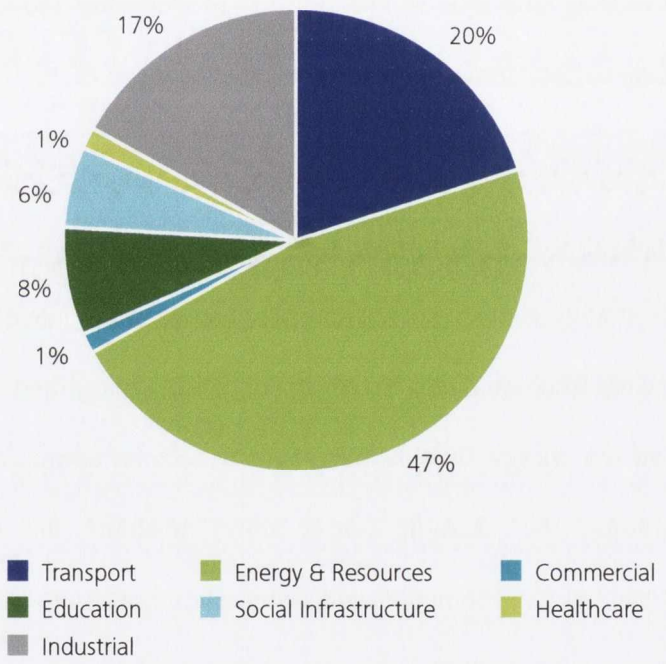


Figure 1 . 13: Construction project value breakdown per sector in Saudi Arabia

(Deloitte & Touche M.E., 2013)

According to AFP News (January 2016), the total cost of the energy subsidy in Saudi Arabia was estimated at $61 billion in 2015. More than half of the electricity generated in the country is attributed to the residential sector (Oxford Institute for Energy Studies, 2013), therefore, over $30 billion is currently spent annually on the residential building

energy subsidy alone with the subsequent adverse impact on the environment and the economy. This suggests the importance of promoting alternative sources for electricity in the construction industry as proposed and modelled in this project (chapter 7). For example, 100,000 domestic dwellings are expected to be built in the coming few years in the King Abdullah Economic City (KAEC), Mecca Province. If the subsidy was to be removed, this project alone would save the government about 570 million USD per year. Moreover, this project could save over 5 billion Kg CO_2 per year if the dwellings were to include the sustainable source of energy (solar PVs) proposed and modeled later in this project. These calculations are based on the current 5,704 USD subsidy granted to each dwelling and the 53,789 $KgCO_2$ of emission reduction per dwelling per year according to the simulation results.

These economic savings and the strong environmental impact associated to the current high (subsidized) consumption can be used to enhance sustainability at governmental level especially as over 2.3 million new homes are planned to be built by 2020 (Sidawi, 2009). This forecasted new building could add approximately a further $13 billion to be spent on the energy subsidy per year, to become approximately $43 billion annually. Furthermore, the example above only considers the residential building sector. Therefore, the environmental and economic impacts are yet stronger. This provides an indication of the extent of the impact that implementing sustainability in construction can have in the country.

1.8. Construction in Mecca

The city of Mecca, also known as Makkah Almukaramah is the capital of Makkah Province in the Kingdom. Mecca is an important cultural and religious centre for Muslims who pray five times daily toward the Kaaba in Al-haram, the holy grand mosque. In fact, Mecca attracts millions of people every year from across the globe as

they perform Hajj and Umrah. Hajj is the Islamic pilgrimage for which around 3.5 million pilgrims gather in Mecca to perform one of the five pillars of the Islam over the course of specific seven days from the Islamic calendar annually. The holy month of Ramadan is also another season that affects Mecca in all aspects of life due to the high volume of visitors during that month. Umrah, is also a short pilgrimage that can be taken any time around the year. Over the last years, the numbers of pilgrims have significantly increased. Mecca sees a growing number of pilgrims from around the world and from within Saudi Arabia every year. Thus, construction demand is increasing rapidly to meet the needs of the city in the short and the long-term. In fact, Mecca's real estate is considered one of the most expensive land banks in the world, where one square meter was valued at $133,000 in 2011(Aljazira Capital, 2013).

Mecca is enjoying enormous support from the country's leaders according to Mecca's mayor Osama Al-Bar. He added that the value of Mecca's projects is estimated at $80 billions where one third of this amount is governmental projects. Construction projects in the city centre are disturbed during the hajj season returning to normal when the Hajj season is over however showing a renewed focus to provide enough houses, transport links and basic utilities to meet the rising demand during the Hajj season.

According to regional projects tracker (MEED Projects, 2014), the 20 largest projects planned or under way in the Mecca region have a combined budget of more than $280 billion. According to MEED (2013), *"That is equivalent to the total value of project activity in Qatar and larger than the entire market in Kuwait, Oman or Bahrain."*

The need for such spending is clear considering the number of people who visit or live in Mecca (MEED, 2013). About 1.7 million Hajj visas were issued to pilgrims, along with about 5.5 million Umrah visas in 2012 by the Saudi Embassy in Washington. Even without devout tourists, the Mecca region would be the most populous in Saudi Arabia

due to economic and social reasons due to the location of the holy places as well as the largest economic port in the economic capital of Jeddah. In 2011, about 7.2 million people were living in the Mecca province which accounts for 25.5% of the country's total population, marginally ahead of the Riyadh region with 7.1 million residents according to the most recent statistics from the Saudi Arabian Monetary Agency (SAMA).

The nature of the tourism market that sees huge numbers of visitors arrive in a very short period of time in Mecca has led to the critical need to move people in and around the area efficiently. As a result, the government is improving Mecca's transport systems. In November 2012, the Development Commission of Mecca & Mashaaer (DCMM), invited firms to compete for the first phase of the Mecca Metro, which involves a 180-kilometre, four-line railway with 88 stations and is part of the wider $16 billion Mecca Public Transport Program (MPTP).

The scheme is part of a wider plan by the government to build a network of new cities around the province although the ambitious vision has not always proceeded smoothly. Some elements of the King Abdullah Economic City (KAEC) project have been cancelled or stalled, including a $3 billions steel plant cancelled by the local Al-Rajhi Steel Industries in May 2013, as well as a $4 billions Education Zone and a $ 4 billions Financial Island, both of which are on hold.

However, other elements of the megaproject are moving ahead. The local Rezaik al-Jedrawi Company was awarded a SR 313 millions ($1 = 3.75 Saudi Riyal) deal to build the first phase of Al-Waha Community, a middle-income housing scheme in the city which will cover around 180,000 square metres containing 650 units. Besides that, large new residential, commercial and mixed-use developments are also expanding in the existing towns and cities of the region according to MEED Projects (2014).

The $20 billion Mecca Gate development planned by the local Al-Shamiyah Urban Development Company on the western outskirts of Mecca is one the biggest existing projects in the city. Once completed, it will provide homes for about 600,000 of national citizens.

A further regional project worth $3.5 billion is the Jabal Omar Development (JOD), located next to the Grand Mosque in the city centre. This scheme will transform the look of the central area involving a collection of 37 buildings. The first three phases are presently under construction, and design is ongoing on the fourth and fifth phases. Additionally, The Grand Mosque is being expanded at a cost of $2.5 billion to accommodate up to 500,000 worshippers in an effort to meet the increasing demand of worshipers every year.

Behind all these schemes are heavy investments in utilities, hospitals and education. Some of these projects rival the biggest real estate schemes in terms of cost. According to MEED Projects, the Saudi Electricity Company (SEC) is spending more than $18 billion on upgrading the power generation and transmission networks in the Mecca province. The National Water Company is also planning to invest SR10.7 billion in water schemes in both Mecca and Taif while investing a further SR15.7 billion in Jeddah.

Regarding the healthcare sector, the $1 billion King Abdullah Medical City in Mecca (KAMCM) will provide 1,500 beds and a range of specialist departments. Nine prequalified bidders submitted their offers for the three-year construction contract in November 2013. At the same time, the Higher Education Ministry is spending about $2 billion on building facilities at Umm Al-Qura University in Mecca, King Abdulaziz University in Jeddah and Taif University in Taif. Table 1.9 shows the largest 20 projects in these areas.

Project	Location	Owner/Developer	Description	Current status	Budget ($m)
King Abdullah Economic City (Kaec)	Rabigh	Emaar, The Economic City	Mixed-use development for up to 2 million residents	Under construction; some elements, including the $4bn Financial Island, are on hold and others have been cancelled	93,000
King Abdulaziz International airport	Jeddah	General Authority for Civil Aviation	Revamp of existing terminals and expansion of airport capacity to 80 million passengers a year by 2035	First phase to revamp existing terminals under way	28,000
Mecca Gate	Mecca	Al-Shamiyah Urban Development Company	New city on the western edge of Mecca for 600,000 people	Project plan approved by governor of Mecca, Prince Khaled bin Faisal, in August 2013	20,000
Kingdom City	Jeddah	Kingdom Holding	Mixed-use development on 2 square-kilometre site, including Kingdom Tower	Piling works in progress	20,000
Mecca Public Transport Programme	Mecca	Development Commission of Mecca & Mashaaer	Four-line metro network and bus rapid transport system	Prequalification bids for the civil construction contract on phase 1 of the metro due by January 2014	16,000
Al-Ruwais regeneration	Jeddah	Jeddah Development & Urban Regeneration Company (JDURC)	Mixed-use development with apartments, villas, offices and shopping malls	Feasibility study under way	13,800
Haramain High-Speed Rail Network	Mecca, Medina provinces	Saudi Railways Organisation	High-speed rail link between Mecca and Medina, via Jeddah, Rabigh and Kaec	Under construction and due to be completed in the fourth quarter of 2014	13,743
Qasr Khozam	Jeddah	Khozam Development Company	Mixed-use development spanning more than 4 sq km in the Al-Nuzlah district of the city	Demolition of existing properties under way	13,331
Jeddah Metro	Jeddah	Jeddah Municipality	Three-line metro running for more than 117km	Engineering and design contract expected to be awarded by the end of 2013	12,300
Al-Shamiyah Mecca development	Mecca	Al-Shamiyah Urban Development Company	Housing for 134,000 residents on a 7.4 sq-km site north of Mecca	Design will start once the expansion of the Grand Mosque is completed	9,300
Thakher City	Mecca	Thakher Real Estate Development Company	Real estate project with 85 towers	Design work completed	8,000
King Abdulaziz Road Project	Mecca	Umm al-Qura for Development & Construction Company	Mixed-use development on either side of main highway into Mecca	Demolition of existing properties under way	6,600
Wadi al-Asla	Jeddah	JDURC	Mixed-use development including residential units, safari park, university campus	At design stage; due to be completed by September 2018	5,866
Jeddah Gate	Jeddah	Emaar Middle East	Mixed-use development with 6,000 residential units, offices and retail space	Construction work under way	4,700
Abraj Kudai	Mecca	Finance Ministry	Mixed-use development with 12 towers comprising 30-45 floors each	Saudi Binladin Group awarded the main contract in mid 2013	3,600
Jabal Omar	Mecca	Jabal Omar Development Company	Mixed-use scheme featuring 37 buildings close to the Grand Mosque	Phases 1-3 under construction; design work under way on phases 4 and 5	3,500
Jeddah Security Forces Medical Complex	Jeddah	Interior Ministry	Medical complex with hospitals, research facilities and residential units	Main contract award expected in fourth quarter of 2013	3,350
Jabal al-Kaaba	Mecca	Abdul Latif Jameel	Six hotels northeast of the Grand Mosque	Anjum Hotel construction completed and concept designs under way for other hotels	2,700
Grand Mosque expansion	Mecca	General Presidency for Haram Affairs	Expansion to accommodate 500,000 worshipers	Construction work under way	2,500
Obhur development	Jeddah	Rayadah Investment Company	Mixed-use development with residential units, schools, hospital, hotel and other facilities	Mohammed Ali al-Swailem Group won main infrastructure package in September 2013	2,500

Table 1 . 9: The 20 largest projects in Mecca Province

(MEED, 2013)

However, most of these projects use conventional materials of high embodied energy responsible for high greenhouse gas emissions. Table 1.10 summarizes the materials most commonly used in current and planned projects in the country, including their properties, use, environmental advantages and disadvantages.

Material	Properties	Use	Environmental Advantages	Environmental Disadvantages
Concrete Blocks	Durable Good acoustic performance Good thermal mass High design flexibility High strength Reusable	Block paving Roofing Wall building	Can be recycled hence associated with less environmental pollution. Resistant to fire	Non-renewable materials Poor insulating properties Requires careful transportation, increasing the transportation cost.
Sand	Durable Non-corrosive Permeable Reusable Thermal Stability	Concrete blocks Masonry mortars Precast stones	Biodegradable Can be obtained locally eliminating or reducing embodied energy. It is resistant to fire since it is not flammable Non-toxic Resistant to fire	Extraction activities are invasive.
Steel	Allows excellent indoor air quality Durable Has a good design flexibility It is a light building material. Resistant to fire Strong	Making construction tools such as chisels, files and dills Reinforcement of building walls. Used in welding	Generates little waste at the construction site, reducing landfill contamination. Iron and steel industry associated with low emission of greenhouse gases. Recyclability 100% of the steel sections can be recycled at the end of use or life. Non-toxic material	Can rust, polluting the environment and damaging materials High energy consumbtion High embodied energy Non-biodegradable Obtained from non-renewable sources
Glass	Durable Resistant to strong wind Strong Translucent Transparent	Used for internal partitioning Used on doors Used on roofs Used on walls Used on windows	Does not produce toxins. It is a fully recyclable building material hence preserves natural resources. Its inert nature prevents reactions with other materials When used doubled or tripled its thermal insulation capacity reduces building energy needs. The acoustic quality of some types of glass controls the amount of noise reaching the building or the outside environment.	High embodied energy In the event of fire, walls made of glass collapse before the occupants are completely evacuated It is a poor material in terms of heat preservation, a characteristic that affects the health of building occupants. Non-biodegradable Uses non-renewable sources for production. Ventilation is an issue since walls made of glass cannot be opened.

Portland cement	Can be made into different designs Durable Has good tensile, flexural and compressive strength Resistant to corrosion	Construction of beams Construction of dams and roads Construction of panels In production of concrete	Can be recycled and act as a recycling medium It is economically sustainable since it is obtained from local sources Resistant to fire	Dry cement is associated with lung cancer as well as respiratory and eye irritation High embodied energy Its production causes harm to the environment through vibration as well as production of noise and dust Its use when wet can cause major skin burns since the material is highly alkaline Poor insulating properties The carbon dioxide produced can lead to green-house effect

Table 1 . 10: Common materials currently used in Mecca's construction

Chapter Two: Construction Project Management and Practices in Saudi Arabia

2.1. Introduction

Saudi Arabia has seen unprecedented construction growth during the last decades, which has attracted construction firms from all around the globe. Therefore, the construction management of projects has not been fully standardized and is largely a function of the creativity and experience of each construction company individually. Due to the different nationalities of the construction professionals, the diversity is very visible in this country.

However, four different types of project management practices are found in Saudi Arabia despite the fact that government projects have to follow the government tender law that includes standard specifications and conditions of contracts. These include the traditional Architectural/Engineering (A/E) type, design-construction manager type, professional construction management (CM) type, and design/build or turnkey type. In fact, the turnkey type is widely used in military construction projects, while the second and third is used in large-scale or mega projects of a special nature such as airports. Moreover, most of the projects that are governmentally funded follow the traditional A/E practice where the owner holds the power to decide on matters related to both changing the contract value or contract period.

Typically, most of the governmental departments write their contracts as lump-sum contracts. A few others follow the competitive bill of quantity-based type of contracts while military projects are negotiated and all other projects are competitive.

Project control systems, however, range from simple manual methods to fully computerized methods using the most high-tech and comprehensive software packages currently used worldwide. Scheduling methods ranging from bar charts to the probabilistic models of Project Evaluation and Review Technique (PERT) and with the majority using the Critical Path Method (CPM) model. The project control system is

sometimes not stated by the contract terms and conditions. Consequently, it is left to the contractors' management to decide what type of project control to be used. Recently, more projects have specified the practical details to be followed in contract administration.

In addition, efficiency and productivity have been a function of the contractor's experience, nationality, source of labour force and type, and the project's location. Generally, the productivity and efficiency of construction firms practising in Saudi Arabia have been improved over the last decades.

2.2. Construction Challenges

A series of problems have occurred due to the huge developments in the Saudi Arabian construction industry. These are discussed below.

Economical Problems

The rate of inflation has jumped to a very high level during the last couple of years due to some factors. These factors impose a great demand on the construction industry, the manipulation and overpricing by foreign contractors, and the incapability of the market to meet the fast growing demand or to handle the available cash flows.

Social Problems

There is an importation of hundreds of thousands of labourers from different cultural backgrounds to Saudi Arabia, a conservative society, which cannot be expected to go unobserved. Indeed, there is a substantial effect on both sides. Because of the social and cultural barriers, foreigners hardly socialize with Saudis and some remained very much isolated from the society in which they lived. Some others felt lonely and somewhat disappointed. This situation has had a tremendous effect on their productivity as well as on their length of stay.

According to The World Factbook (2014), more than 27 millions are the total population in the country where 30% of them are non-nationals and the majority work within the construction industry. In fact, a question remains open on whether the 2013's correction of visa status clampdown on non-nationals workers in the kingdom will slow progress on some of the sectors in the country especially the construction sector. An amnesty period for expatriate workers to correct their visa status or leave the country specifically for those who work on different jobs than the jobs that they came to work for. At least in the short term, some difficulties are likely to occur in the Saudi construction sector because of its dependence on the plentiful cheap foreign labourers.

According to Samba bank, on their update on the Saudi economy in November 2013, *"the crackdown on illegal expatriate labour ... might disrupt sectors such as construction and retail"*. In addition, *"If the disruption persists, the government will have little option but to change its approach. There is high demand for houses, hotels, offices and factories across the kingdom that needs to be addressed. With its large settled population and huge, regular influxes of religious tourists, that is as true in the Mecca province as anywhere else."* (MEED, 2013).

Technical Problems

Many technical problems have been exposed due to the new massive structures in the country. *"Most of these problems are related to the local geotechnical formation. These include limestone solution cavities, high water table, and swelling of clay fills, to mention just a few."* (Al-Jarallah, 1983).

Additionally, harsh desert climate conditions are the cause of some technical problems in Saudi construction. Some other technical problems are basically due to the different backgrounds of consultants and contractors who are familiar with a variety of codes of practice and standard specifications.

Management and Legal Problems

One main problem facing construction execution is that most of the construction projects are planned to be executed on accelerated construction schedules especially governmental projects. In fact, foreign contractors, particularly those who are new in the market, try to use imported control systems that ignore Saudi local conditions especially when they face technical problems due to the code of practices that they are not familiar with. For example, some contractors mix and pour the concrete during the daytime instead of night time, which is the best time to avoid the extreme hot temperature during the summer. The misjudgement, in fact, results in many legal and administrative problems including cost overruns, connection problems, and delays.

2.3. Stakeholders Involved in the Construction Sector in Saudi Arabia

There are several stakeholders in the Saudi public construction sector. The main stakeholders include the Public Authority, Project Owners, Contractors, Ministry of Health, Ministry of Labour, and the Ministry of Planning.

The government owns the public projects. The projects mostly reflect the strategic planning of the Saudi infrastructure. In fact, all the projects need to be governmentally approved which may take several months for final approval.

The Saudi Arabian public construction projects involve several organisations in the country. The responsibilities of the organisations are to implement the government's public strategies as well as to hold the financial power over the project execution since they are the owners of the public projects. The main project owners include Royal Protocol Engineering Department, Ministry of Housing and Public Works, Ministry of Transport, Ministry of Water and Electricity and Ministry of Municipalities and Rural Affairs.

Contractors carry out the majority of Saudi public projects. There are a great number of contractors in the Saudi Arabian construction industry and market. Local, regional and international contractors are all working in the construction of public and private projects. However, contractors in Saudi Arabia are classified mainly on their financial capability.

In Saudi Arabia, it is the responsibility of the Ministry of Health towards projects' environmental impact on the local environment. From the project implementation process, the Ministry has to check the project locations and main wastes and disposals for public health purposes.

The majority of the Saudi construction market's labourers is non-national. This forces the contractors to use a large number of non-nationals in the project. Consequently, it requires contractors to follow the procedures and requirements of the Ministry of Labour. Another issue related to this is the current policy of the Ministry of labour, which states that a certain number of Saudis have to be employed in such an organisation in order to reduce and possibly eliminate the rate of unemployment.

Basically, the country's public project strategy is a responsibility of The Ministry of Planning. They have a national group of plans where each plan is a five-year strategy plan. For each five-year strategy plan, the ministry identifies the type, size and location of the needed public projects across the country. Therefore, the Saudi Ministries need to link and coordinate their projects with the Ministry of Planning each time when a project is needed.

2.4. Factors Affecting Construction in Mecca

Mecca is no exception to the construction issues in Saudi Arabia. However, its value, importance, and location have led to give Mecca some special characteristics. Sami

Barhamin, former Secretary General of Development Committee of Makkah and Mashaar Mukkadash, came up with a list of factors that affect construction practices in Mecca as follows:

Location and Topography

At large, topography refers to the numerous mountains, Jabals, and valleys forming the Mecca region. Moreover, steep mountains in the city create a great difficulty in construction work especially the excavation. On the other hand, valleys are subject to floods during heavy storms of rain.

Barhamin (1986), indicated that Mecca's mountains, Jabal in Arabic, include: Jabal Hira, Jabal Thawr, Jabal Abu Qubays, Jabal Qaa'l-et-Jiyad, Jabal Omar, Jabal Al-Kaa'ba, Jabal Hindi, and Jabal Adhakir which form the topography of the city of Mecca. Considering the mentioned rough topography, construction in Mecca is restricted mostly to the valleys and along the slopes of the mountains, which is obvious in the city. This, in turn, would require massive excavation and levelling that would lead to destruction of the natural landscapes of Mecca and produce a huge environmental impact on the whole city. Another impact is the increase in the overall construction costs. For instance, special equipment is required to excavate the hard igneous rocks, (mostly granite and basalt) forming the mountains. In addition, more time and labour are needed to move the equipment to the steep sides of the highlands.

Structure and Buildings Fabric

Scientifically, the structure and building/urban fabrics refer to the whole characteristics of an area in terms of the size and shape of its major roads, streets, and constructions. Mecca has a unique structure and buildings that contain the Kaa'ba and the Holy Mosque, which, many have a strong desire to live close by. Thus, the central area around the Holy Mosque is a dense zone that includes residential spaces with seasonal housing

units and commercial shops. In contrast, other areas than the centre are with less density.

Climate and Temperature

The weather of Mecca is affected by its nearness to the Red Sea and the mountains of Taif, Chain Mountains of Sarwat (CMS) as an example. The climate is hot and humid in the summertime and cold in the wintertime. It is about 45° C in the summer as a maximum temperature. Furthermore, in the summer evaporation may reach 16mm/day and in the winter 6mm/day while wind speeds are high. Construction costs increase in Mecca because of the hot weather that leads contractors to provide air-conditioning systems for offices and residential units. Additionally, certain equipment is not designed to operate in high temperature environments. Moreover, mixing and placement of concrete require special treatment in hot weather like adding some special types of additives like ice.

Building Laws and Regulations

The building regulations and laws specify items related to site preparation, maximum area of a building, ground floor level in relation to street level, number of floors, ventilation systems, electrical wiring, color of exterior walls, and fire and flood protection. Actually, no building can be constructed without a permit from the local municipality. Construction methods, materials, and equipment must comply with the city's building regulations. The current laws and regulations, in fact, do not support sustainable construction where this research aims to promote that in terms of suitable sustainable construction practices based on the specific needs of this part of the world as mentioned in the significance of the research.

In fact, construction in Mecca is so restrictive due to the sensitivity of the city as a holy place that attracts millions of people every year. This is also because of the amount of construction activities going on in the city in which needs more attention. However,

sustainable principles proposed later in the research could lead to preserve the economy and the environment as well as the community's health.

Master Plan

The master plan is the official document adopted by the local government as a guideline to for the future developments of the community. As a result, construction companies use the master plan to set their long-term policies. The master plan could also be strengthened to include stipulations and requirements to promote sustainable construction in the future, as this research will suggest later.

Construction Problems Among Agencies

The following problems among agencies working in Mecca's construction industry have been identified according to former Secretary General of Development Committee of Mecca and Mashaar Mukkadash, Sami Barhamin.

- *"Cooperation is not clearly defined, and sometimes is missing. Indeed, lack of coordination causes waste of time and money. As an example, roads in the Holy city of Mecca are continuously excavated for placing pipes or wires, paved and later on dug up again for other public services.*
- *Most projects are undertaken by private contractors. The work of government agencies is limited to official communication related to time schedule and completion date.*
- *Tenders are often awarded to contractors submitting the lowest bid regardless of their skills and experience. This drawback has a negative impact on the quality of the work.*
- *Some projects have to be suspended temporarily during Umrah and Hajj seasons.*
- *Lengthy administrative procedures at ministry level cause suspension of projects as a result of delay in allocating the needed funds."*

Changing methods and techniques in current practices could solve some of the mentioned problems. For example, only inviting tenders from lists of pre-qualified contractors can avoid the problem that mentioned in the second bullet point above. Others may need to rethink about in order to better handle current and future challenges.

Land-Ownership Problems

There are two types of land in Mecca that include state-owned land to ministries such as Education, Defence, Hajj, Agriculture, National Guard. The other type of lands is the private–owned land. Generally, land values in Mecca are very expensive as explained in the first chapter. In fact, more than two-thirds of the total cost of public projects as roads, tunnels goes as a compensation to land owners according to Barhamin. Moreover, when planners base their calculations on the basis that certain land is not owned by anyone, sometimes later on, a person or an entity comes and claims his ownership to the land resulting the construction to stop or delay until a dispute is resolved.

Restriction on Non-Muslim Labourers

Non-Muslims are not allowed to enter or work in the Holy city of Mecca for religious reasons; consequently, all labourers working in Mecca are Muslims. Thus, the religious holidays of Ramadan and Hajj, and the daily breaks for prayer altogether affect the construction activities. In fact, the degree of competition among contractors is also reduced due to the restriction on non-Muslims. In fact, this less competitive market would increase the cost of bids and/or decrease the total quality of the construction work. Naturally, this negative outcome would be eliminated if skilled Muslim workers dominate the market.

Ramadan and Umrah Seasons

According to experts, the holy month of Ramadan affects the duration time and the total costs of the construction projects. The working hours during the month of Ramadan are

36 hours/weak, including night work, instead of 48 hours/week compared to the other months of the year. In Ramadan, where Muslims fast from before sunrise to sunset, labourers' productivity would be less than average days. Besides that, the last ten days of Ramadan are always crowded with pilgrims coming to perform Umrah, which makes it harder for construction works and workers.

Hajj (Pilgrimage)

The Hajj season has its advantages and disadvantages on construction. Disadvantages include the increase of construction costs due to crowds of people and traffic jams. For illustration, construction in areas close to the holy Mosque, Al-haram, has to stop because labourers that live some distance away from Al-haram cannot reach the site. In addition, it is impossible for materials that are stored in places outside of Mecca to reach the site, especially in the central area, during Hajj season. Other disadvantages are time breaks where construction has to stop for Hajj and Eid vacations.

On the other hand, advantages of Hajj on construction include increasing the demand for more modern roads, tunnels, bridges, buildings; continuous demand for effective maintenance to the present facilities; improving the economical environment in Mecca; increasing the capital expenditure on construction projects.

Government Budget-Time Conflict

The announcement of the government budget on the 22nd of December every year is imposing an extra effort on construction companies to complete projects in time and within the available budget. It has a strong effect on planning and scheduling time.

However, solutions to factors mentioned can be found in the conclusion chapter later on by enhancing sustainable principles especially during bidding process and pre-construction phases and not to forget the whole life cycle of a construction. This would eventually reduce a number of obstacles facing the achievement of more sustainability

and also would pave the way to better handle construction activities in the country.

Chapter Three: An Overview of Sustainability in Construction

3.1. Introduction

In 1972, the interconnections between economic growth and the environment were acknowledged in the United Nations Stockholm Conference on the Human Environment. Fifteen years later, during the World Commission on Environment and Development (WCED), the UN-sponsored Brundtland Commission released a report called *"Our Common Future"* which captured broad concerns about the environment and poverty in many countries around the globe. The economic development cannot stop but should change its course to fit within the planet's ecological limits, the report indicated. It also propagated the term "sustainable development", defining it as *"development that meets the needs of the present without compromising the ability of the future generations to meet their needs"*. Through the World Commission, an agenda for environment and development in the 21st Century, Agenda 21, was adopted and identified each nation's right to pursue social and economic progress. This agenda, in fact, confirmed that sustainable development is the integration of economic, social, and environmental aspects. Agenda 21 also requires countries to adopt national strategies for sustainable development, which build upon and correspond with various local economic, social, and environmental policies and plans within each country. Furthermore, the World Summit on Sustainable Development (WSSD) in 2002 was convened in Johannesburg to renew a worldwide commitment to sustainable development.

Saudi Arabia is committed to effectively applying sustainable development within its national development plan. According to Tahir and Ahmed (2013), the government has made some progress in its socio-economic development, gender equity, standard of living, health, education and environmental legislation.

According to Tahir and Ahmed in Saudi Arabia, environmental and sustainability research can play a significant role in some areas including national air quality

management plan, sustainable water resources planning, sustainable energy planning, marine pollution and ecological impact, and waste management. In the last decade, sustainable construction has received attention by the Saudi government. In 2009, The Saudi Green Building Council (SGBC) was established. This is a non-profit-organization led by the King Saud University and funded by a group of professionals and academics. In 2010, King Abdullah's initiative, The Saudi Green Building Forum (SGBF) that supports sustainable construction nationwide was lunched. SGBF aims to promote and facilitate sustainable building practices and knowledge across the country; and preserve urban identity and environment through creativity and innovation. However, the progress and accomplishments of the SGBF are poor and limited. In the Middle East and North Africa (MENA), there are some factors which lie behind the limited progress on creating sustainable developments (Jones Lang LaSalle Inc., 2013). These factors are as follows:

- Lack of legislation to urge change and introduce new practices in different markets
- Absence of any financial premiums for sustainable initiatives
- Subsidization to energy (gas and oil)
- Low water and waste disposal costs
- Limited awareness of environmental issues among local and regional stakeholders

According to Mahroum (2013), these factors are important because the country's ecological footprint is estimated at 4.5 global hectares per capita, which is about twice the world average. Saudi Arabia, in fact, is ranked among the top 20 most environmentally challenged countries in the world.

3.2. Sustainable Construction Materials and Techniques

3.2.1. Sustainable Materials

Building materials and technologies along with building practices have changed through the years. They began with the use of natural materials like stone, soil, thatch/leaves, and unprocessed timber. However, problems associated with durability and speed of construction led to the mainstream uptake of modern processed materials. Contemporary, energy-consuming materials used in construction include glass, Portland cement, polymers, and others. In fact, revolutionary changes brought in the construction practices were due to Portland cement and steel (Venkatarama Reddy, 2009). Later, plastics and plastic products entered the construction industry leading to further development in building materials and technologies. Table 3.1 shows developments in building materials and technologies from early years with regard to energy consumption. It is obvious that the move from the sustainable materials of the past to the modern materials of global construction implies heavier energy and natural resource consumption. Many modern materials have high embodied energy, which is against sustainable principles. The choice of a building material also needs to consider its overall impact on the environment including carbon emissions and other greenhouse gases that contribute to global warming as well as the high rate of consumption of natural and raw material.

Prior to 4000 BC	4000 BC–1800 AD	1800 AD–to date
Soil, stones, reeds/ thatch, Sun dried bricks/adobe, unprocessed timber	Burnt clay bricks, lime, cast iron products, lime-pozzolana cement	Aluminium, steel, glass, Portland cement, plastics, other smart materials, nano-materials, etc.
Zero-energy materials	Medium-energy materials	High-energy materials

Table 3 . 1: Energy consumption and developments in building materials (Reddy, 2009)

Building materials need to be sensibly considered from harvesting through the reuse or demolishing of the building. According to Yudelson (2007), green building materials should be used in construction as they are less harmful to the building occupants and the environment. A universally and univocal accepted definition of 'green building materials' still does not exist (Franzoni, 2011). In fact, green building materials are generally considered as environmentally friendly (Kubba, 2010) or environmentally responsible materials (Spiegel and Meadows, 1999). Sustainable materials or products are those that use natural local renewable resources or recycled ingredients, recycle any waste generated by their processes, are biodegradable, have low embodied energy, have minimal derivation from petrochemicals, and are designed for reuse and recyclability (Woolley and Kimmins, 2000). In addition, green building materials are also energy and water efficient, durable, nonhazardous, nontoxic, and environmentally responsible in manufacturing, occupancy and destruction.

In order to enhance sustainability in construction, the sustainability of materials should be considered in its three phases of life cycle; Pre-Building Phase; Building Phase; and Post-Building Phase (Kim and Rigdon, 1998). Figure 3.1 shows the three phases of the building material life cycle in more details.

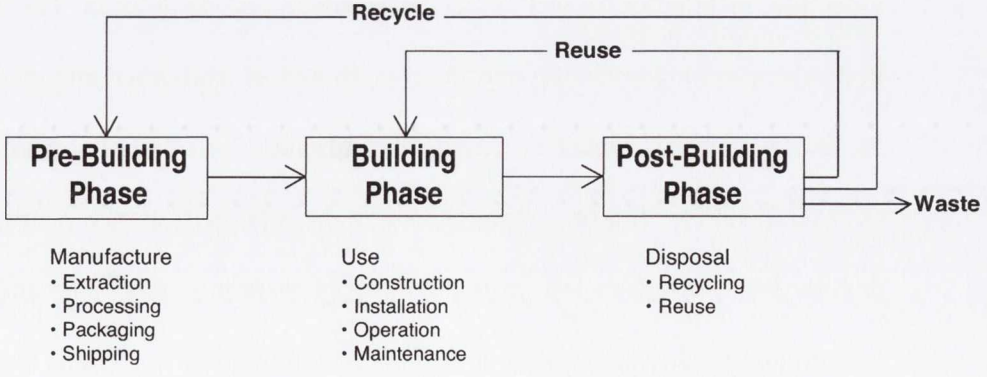


Figure 3 . 1: Phases of the building material life cycle

(Kim and Rigdon, 1998)

In the selection of sustainable building materials, there are some criteria to be considered including construction techniques, manufacturing processes, raw material extraction and harvesting, and elimination of demolition waste (Kim and Rigdon, 1998). Figure 3.2 illustrates the key features according to same source.

Green Features		
Manufacturing Process (MP)	**Building Operations (BO)**	**Waste Mgmt. (WM)**
Waste Reduction (**WR**)	Energy Efficiency (**EE**)	Biodegradable (**B**)
Pollution Prevention (**P2**)	Water Treatment & Conservation (**WTC**)	Recyclable (**R**)
Recycled (**RC**)	Nontoxic (**NT**)	Reusable (**RU**)
Embodied Energy Reduction (**EER**)	Renewable Energy Source (**RES**)	Others (**O**)
Natural Materials (**NM**)	Longer Life (**LL**)	

Figure 3 . 2: Fundamentals to the green features of sustainable building materials (Kim and Rigdon, 1998)

Buildings are constructed with a range of building materials and each one consumes energy throughout its stages of manufacture, use, and deconstruction (Escamilla et al, 2012). These stages contain the raw material extraction, manufacturing, transporting, assembly, installation as well as its disassembly, and demolition. The energy consumed in production (in conversion and flow) is known as 'embodied energy' and it represents the environmental impact of energy consumption and carbon emissions of materials (Koskela, 1992). Building materials of high-embodied energy result in more carbon dioxide emissions than low embodied energy materials (Gonzalez and Navarro 2006). According to many studies, embodied energy and carbon emissions are important in the context of buildings and construction materials (Rawlinson and Weight, 2007). This is essential because materials have direct and indirect impacts on the environment and this should be taken into consideration during the material's life cycle from harvesting to

disposal stages. The total life cycle energy of a building involves both embodied energy and operating energy (Cabeza et al. 2013). The embodied energy is related to building materials during all processes of production, on-site construction, and final demolition and disposal. Whereas, the operating energy is expended to maintaining the inside environment through processes such as heating and cooling, lighting and operating appliances while building in use (Cabeza et al, 2013).

Common construction materials impact the outdoor as well as the indoor environment. Common construction materials and their embodied energy and CO_2 emissions are presented in table 3.2 (Kilbert, 2007) and (Mulavdic, 2005).

Material	***Embodied energy MJ/kg***	***CO_2 emission kg/kg***
Aggregate	**0.1**	**0.16**
Concrete	1.3	0.1311
Brick	**2.5**	**0.189**
Plywood	10.4	4.2
Glass	**30.3**	**0.748**
Aluminum	227	9.964
Steel	**32**	**2.95**
PVC	70	2.6904
Plastics	**61**	**2.2**
Timber	3	0.003
Lime	**6**	**1.352**
Cement	5.8	0.9638
Gravel and sand	**0.05**	**0.0018**
Ceramics	5	0.349

Table 3 . 2: Common construction materials and their embodied energy and CO2 emission (Kilbert, 2007. & Mulavdic, 2005)

As aforementioned in Chapter One, the most common materials currently used in the Saudi Arabia's construction include products that impact the environment starting at

extraction, through processing and manufacture, maintenance and refurbishment till the end of their life and disposal. These include Portland cement, glass and steel, which have high embodied energy and CO_2 emissions (Table 1.10).

Materials commonly used in Saudi Arabia are local (Table 1.10). For Example the steel and iron industry is serving the country as well as the Middle East and North Africa. There are several steel manufacturers, and the Rajhi Steel Industries Limited (Rajhi Steel) and the Hadeed Saudi Iron & Steel Company are the main leaders of steel industry not only in Saudi Arabia but also in the region. In addition, cement products like Portland cement are locally produced in Saudi Arabia. There are many cement factories across the country and the main providers are the United Cement Industrial Company, City Cement Company, Qassim Cement Company (QCC) and Yanbu Cement Company. Other materials like glass and aluminum are also locally produced in Saudi Arabia but with less coverage on a regional scale when compared to cement and steel products. Although these materials are locally produced giving low embodied energy and CO_2 emissions when transporting, they still have high embodied energy and CO_2 emissions (on production) when compared to other materials like earth and recyclables. Still, data on how much these materials harm the environment is not yet available in Saudi Arabia as there is currently little concern on the environmental impact of materials thus the reason of this study.

Figure 3.3 shows the different stages of any construction product/material's life cycle. Nowadays, sustainability evaluation in the world is undertaken using the Life Cycle Assessments (LCA). As defined by the International Standard ISO 14040, LCA, this is a *"compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle."* Figure 3.4 shows a building's life cycle according to European Standard EN 15978 (Coldstream Consulting, 2014).

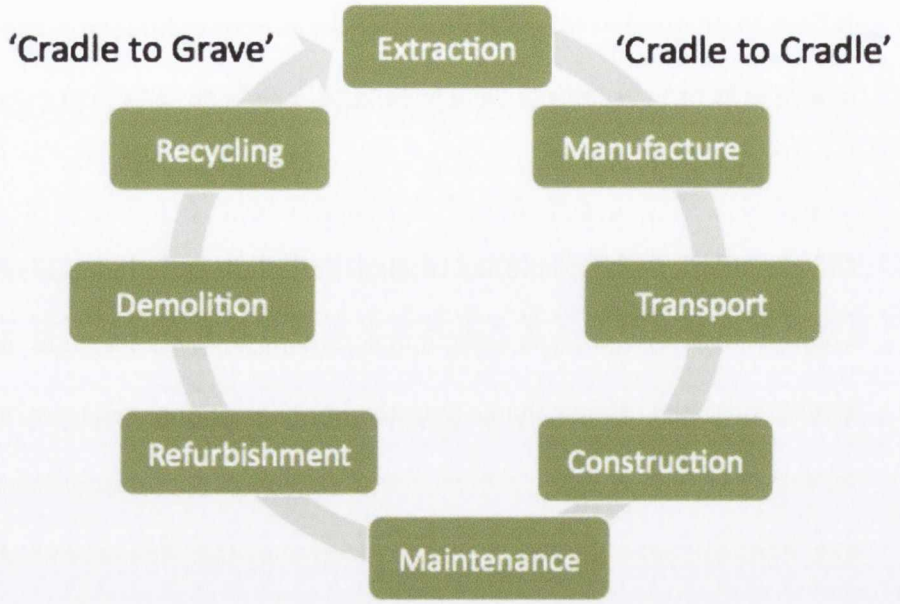


Figure 3 . 3: Life cycle of a construction product

(Construction Products Association, 2012)

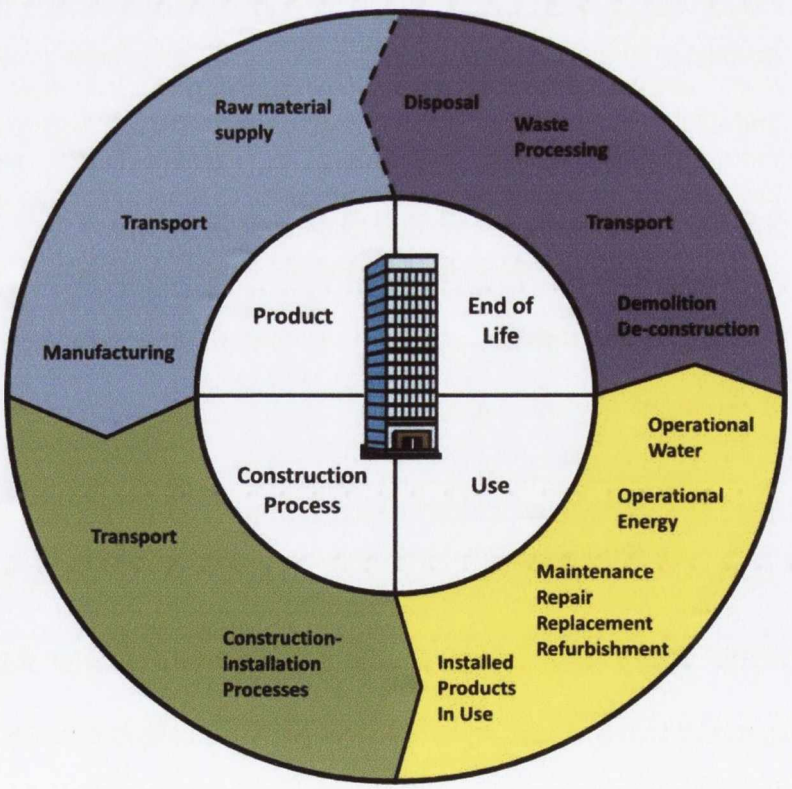


Figure 3 . 4: A building's life cycle according to the European standard EN 15978

(Coldstream Consulting, 2014)

Sustainable building can reduce resource use (Calkins 2008). Reduction in material at the design phase can also substantially lower the consumption of resources. For instance, smaller structures featuring smaller decks, thinner slabs and walls, and cable balustrades rather than hollow steel tube rail are crucial.

The use of sustainably harvested or mined materials from manufacturers that took steps to eliminate or mitigate air, water and soil pollution from their raw material acquisition is also valuable in sustainable construction. Local materials are also sustainable as transport not only requires a tremendous amount of fuel energy but also contributes to both water and air pollution. Other considerations include materials that pose no human health risks unlike adhesives, sealers, finishes, and coatings contain volatile organic compounds (VOC) and other harmful chemical ingredients lead to air and groundwater pollution.

3.2.2. Earth Construction

Earth constructions have taken place across many countries for approximately 6000 years (Graham, 2004). According to Pacheco-Torgal and Jalali (2012), earth construction incorporates several techniques as follows:

- Wattle and daub
- Cob
- Rammed earth (including earth projection)
- Earth bricks (adobe) or compressed earth blocks (CEB)

In the wattle and daub technique, the earth (mixed with water and straw) is forced against a woven lattice of wooden strips. This technique has been used for almost 6000 years (Pacheco-Torgal and Jalali, 2012). The cob technique involves mixing earth with straw and water to form masonry walls layer by layer. According to Quagliarini and

Lenci (2010), adobe is a very simple earth building technique being the reason most ancient constructions were made of adobe worldwide. Saudi Arabian ancient builders used adobe as one of the main materials for building. The word adobe, in fact, came from the Arab ''attob'' that means sun-dried brick (Rogers and Smalley, 1995). Amongst these types of earth construction techniques, Saudi Arabia's old builders mainly used cob and adobe (chapter One). Adobe was the earth technique most commonly used while rammed earth was used occasionally. As it can be seen from Figure 3.5, over two thirds of the extension of Saudi Arabia are areas with suitable earthen materials and have buildings built with earth (The Auroville Earth Institute, 2016).

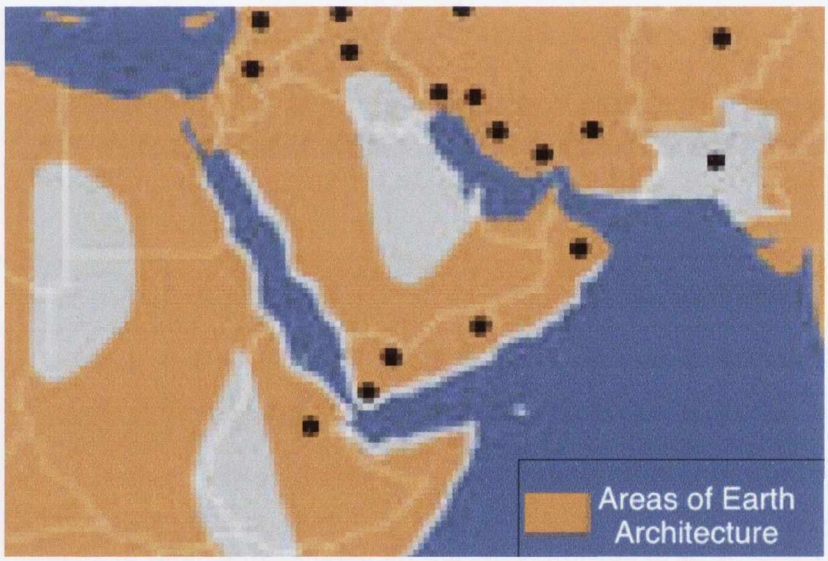


Figure 3 . 5 : Areas of Earth Construction and Earth Materials Availability in Saudi Arabia (The Auroville Earth Institute, 2016)

Types of soil in Saudi Arabia are provided in Figure 3.6 below. Types of soils in Saudi Arabia are mainly loam, sands and loamy sands. Therefore, Saudi Arabia has the potential to use earth for building as these types of soils had been used in the past as discussed earlier in chapter 1. According to the Auroville Earth Institute (2016), sandy soils can be used for rammed earth if the soil is cohesive enough and has enough clay. In

fact, stabilization (approximately 5%) will increase the cohesion when fresh and the resistance when dry based on same source.

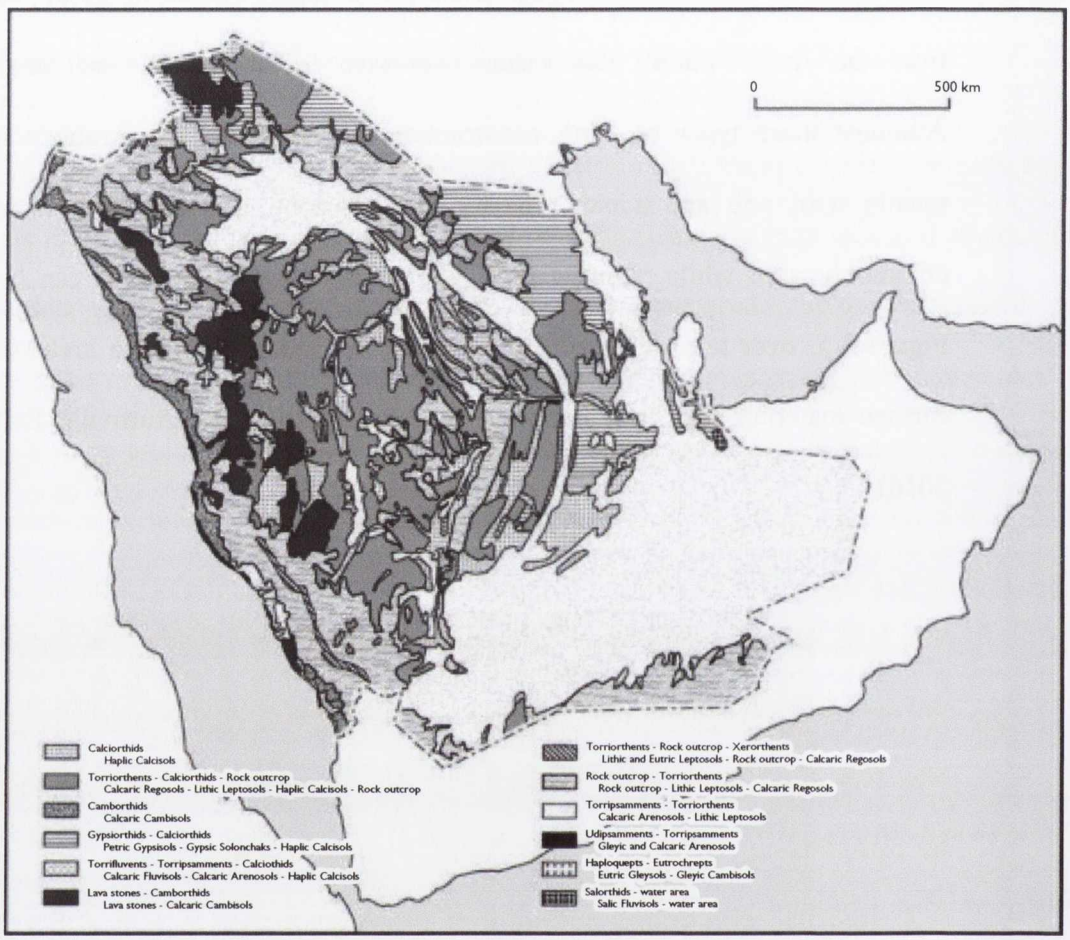


Figure 3 . 6: Soil Map of Saudi Arabia

(Vincent, 2008)

Although earth constructions are numerous throughout the world and currently revived across Europe, America and Australia, they have not yet been standardized in many countries. Saudi Arabia lacks from earthen materials standards. However the existence of building standards and codes of practice are amongst the most important steps toward the reintroduction of construction techniques and methods. In particular, in Saudi Arabia, putting together such guidelines has great potential to increase sustainability in construction, simultaneously benefiting from old builders practices and the local availability of raw material in many regions.

In fact, some countries have begun to standardize earthen materials and methods. For example, New Zealand has a comprehensive suite of earth building standards (NZ Earth Building Standards), which means that any building designed and built in accordance with them automatically meets provisions of the New Zealand Building Code. The Standards are as follows:

- NZS 4297:1998. Engineering Design of Earth Buildings (Specific Design).
- NZS 4298:1998. Incl Amendment#1 2000 Materials and Workmanship for Earth Buildings.
- NZS 4299:1998. Incl Amendment#1 1999 Earth Buildings Not Requiring Specific Design.

The NZS 4297 "Engineering Design of Earth Buildings" is designed for engineers and provides the data and formula necessary to successfully engineer earth walled buildings. However, the NZS 4299 "Earth Buildings Not Requiring Specific Design" is designed for earth building designers. It allows the design of relatively simple earth buildings that fall within its limits with no need of specialist engineering.

Australia also has some standards for earth construction. HB 195-2002 The Australian earth building handbook is the reference for this. It is a joint venture between Professor Peter Walker of Bath University and Standards Australia in 2002. The handbook sets out principles of accepted good practice and recommended design guidelines for lightly loaded, primarily single and two story buildings.

However, in order to start an introduction of earth standards, there are two models that can be seen worldwide. Initially a national standards organization can develop an official standard, as has happened in New Zealand. Alternatively, a group of interested entities with technical expertise can produce an agreed document that can later receive

official acknowledgment, such being the case in Germany (Little and Morton, 2001).

Amongst the methods of earth construction, rammed earth was selected to be modelled in this study. As aforementioned, this hasn't been the main historic form of earth construction in Saudi Arabia however, this method of earth construction is modelled in this research, as it is the method that results in more homogeneous properties and can be better standardized to comply with the strength and durability requirements of new construction and thus become part of mainstream construction. Rammed earth has been widely used in the past in different regions in the world. Outstanding historic examples include the Alhambra of Granada, Spain c.1200; Shibam in Yemen and the 19th c. Great Mosque of Djenné, in Mali. Rammed earth is probably the earth construction method most used today, as compaction allows to achieve greater strength and durability making building more consistent.

Globally, a large number of rammed earth buildings have been constructed in the recent past (Reddy, 2009). Rammed earth construction consists of forming hard walls by compacting processed damp soil in progressive layers in a temporary formwork (Maniatidis and Walker, 2003) (Figure 3.8). Non-stabilized rammed earth is made from soil, sand, and gravel whereas stabilized rammed earth includes additives such as cement or lime. Non-stabilized rammed earth walls imply nearly zero carbon emissions. The drawbacks of non-stabilized rammed earth walls include strength loss on saturation and erosion due to wind-driven rain have led to the addition of additives (Reddy, 2009). Non-stabilized rammed walls are usually thicker, approximately 400 mm, and a good protection from exposure to moisture is needed to preserve their durability.

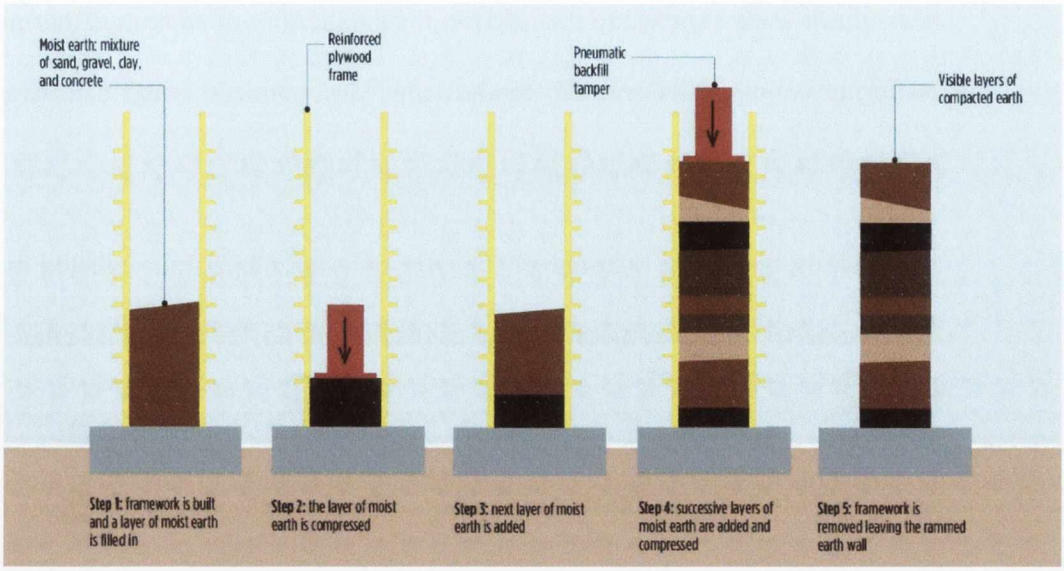


Figure 3 . 7: Techniques of building with rammed earth

(iagram.com, 2015)

Nevertheless, advantages of rammed earth construction involve low embodied energy, use of recyclable materials and local availability of bulk materials, offering of a wide variety of textures and finishes. Additionally, in case of stabilized rammed earth, walls strength and wall thickness can easily be adjusted.

In fact, rammed earth is a viable material as it features low embodied-energy and a thermal stability and durability as envelop for semi-arid and desert climates (Gonzalez, 1999). Moreover, rammed earth is well matched to warm and dry climates such as that in Saudi Arabia due to its high thermal mass and moisture susceptibility (Fix and Richman, 2009).

Rammed earth has outstanding hygrothermal properties. The properties of rammed earth that best describe its hygrothermal performance are moisture storage, vapour permeability, liquid conductivity, thermal conductivity and specific heat capacity (Hall and Allinson, 2009). Earth is a porous and hygroscopic material that contains active clay minerals, therefore earth walls absorb water vapour from the air when relative humidity increases and this moisture is released once the humidity falls. As it is usual practice to

leave earth walls exposed to the interior, the availability of combined thermal and hygric buffering acting as passive air conditioning is maximized when compared with other materials such as brick or concrete (Hall and Allinson, 2009).

Due to these and other advantages (chapter 6), rammed earth is selected in the research as a sustainable element for further investigation in the Saudi Arabian construction industry.

Stabilized Mud Blocks (SMBs) are energy efficient and green alternatives to burnt clay bricks. SMBs are solid blocks manufactured by compacting soil, sand, stabilizer (cement or lime) and water. The compressive strength of a block greatly depends upon the density of the block, soil composition, and ratio of stabilizer. One of the major advantages of SMBs is their energy efficiency as they do not require burning, providing 60–70% energy saving when compared with burnt clay bricks (Reddy, 2009). Another advantage is the decentralization of production that makes production on site feasible.

3.2.3. Other sustainable Techniques

Sustainable construction techniques are many, however, Sundblad (2015) indicated the most global sustainable practices as follows:

- Build nearby alternative transportation
- Decrease environmental tobacco smoke
- Determine minimum level of indoor air quality performance
- Fit energy and water efficient appliances
- Install big windows that deliver plenty of fresh air and natural light
- Install low-emitting carpets
- Low VOC paints
- Plywood processed with no use of formaldehyde

- Proper site selection and prevention of pollution on the construction site like prevention to build on a floodplain, threatened animal habitat, prime farmland, or building too close to wetlands
- Provide space for storage and recyclables' collection
- Reuse or recycle construction materials

It is generally assumed that approximately 80% of the greenhouse gases produced by constructions are released through energy consumed during the life of a building. As a result, insulation is becoming increasingly popular. Insulation lowers heat transfer through built fabrics. Thus, ventilating, air-conditioning, and heating can be designed with smaller-capacity equipment resulting in additional savings (Mir Concrete Products Limited, 2015). Natural insulation materials of low embodied energy made from organic, renewable resources are green alternative to synthetic insulation including VOCs or chemicals. These include sheep's wool, cellulose, hemp, wood fibre and expanded clay aggregate (Anand et al, 2012). In addition they are biodegradable and can be recycled and reused. They also have the benefit of being easy to handle, safe to use and install in addition to being allergen-free and non-toxic. Their hygroscopic properties allow the insulated building to 'breathe' through humidity regulation, a phenomenon that reduces condensation problems (Kamseu et al, 2012). In addition, a new sustainable thermal insulation has been introduced in Saudi Arabia. This type of insulation is called Knauf Insulation mineral wool with ECOSE® Technology. The Knauf Insulation Company provides this type of insulation. In fact, Chapter 6 provides more details on this thermal insulation material with justification on why this was selected for modeling.

A further sustainable construction technique is the application of green roofs, which are the integration of plants and their supporting structures in a construction's roof (Friedman, 2012). Although plants have been used in building for centuries, from the

hanging gardens used in Nineveh to the sod roofs of Europe, currently, they are featured as eco-roofs, living roofs or green roofs (Dalley, 2013). There are two basic types of green roofs: intensive living roofs and extensive living roofs. Intensive living roofs utilize shrubs and trees between 1 and 15 feet in length. Extensive living roofs utilize low-lying plants between 2 and 6 inches in length. Sustainability of green roofs is based on the fact that they can increase energy efficiency of buildings by insulating them in winter and cooling them in summer.

Green roofs also known to filter toxins found in water and air in addition to reducing carbon dioxide emission (Yanling & Roger, 2014). A green roof can provide a habitat for local flora and fauna, help manage storm water, reduce the heating demand in winter and the cooling load in summer, create usable space, and enhance the aesthetic value and comfort of a dwelling. Because roofs represent approximately 40 to 50 percent of the surfaces in urban areas, green roofs have an important role in drainage and, as a result, water management as well (Lawlor et al. 2006).

Using certified wood is sustainable practice. According to Forest Stewardship Council FSC (2015), the FSC certification ensures that products come from managed forests that provide environmental, social and economic benefits responsibly. The use of wood that is generated locally is considered as sustainable material by many sustainability institutions globally.

In relation to the increase of sustainability in construction, it is also advisable to construct buildings near basic services. In addition, the construction process should be characterized by the reuse and recycling of construction materials.

3.3. Sustainable construction regulations

Due to an increase of sustainable building in the world through the use of appropriate materials and practices, several organizations have come up with codes, standards and rating systems. These have been developed with the aim of giving consumers, building professionals and government authorities confidence when embracing sustainable construction. In some countries, codes are found in written form for adoption by the local governments as bylaws in a bid to reduce the impact of buildings on the environment (Howe & Gerrad, 2010).

The International Green Construction Code (IgCC), which is provided by the International Code Council (ICC) is a great example of sustainable construction regulation and practice. According to ICC (2016), the IgCC is the first model code to involve sustainability measures for the whole construction project and site. It concerns the project from design through construction, certificate of occupancy and more. The IgCC code is projected to make buildings more efficient, reduce waste, and have a positive impact on health, safety and community well being.

Consumers are able to use sustainable building rating systems to determine the level of environmental sustainability of a certain construction. BREEAM is the United Kingdom's rating system, which refers to the Building Research Establishment Environmental Assessment Methodology while Leadership in Energy & Environmental Design (LEED) is used in both the United States and Canada. In addition, Germany is using the German Sustainable Building Council (DGNB) and Japan is using the Comprehensive Assessment System for Built Environment Efficiency (CASBEE) as a green buildings rating system. Credits are awarded to buildings with regard to optimal characteristics. The general determination of the level of sustainability is based on the number of credits awarded. Optimal characteristics include those that support

sustainable construction in categories such as occupational health, comfort, sustainability of building materials, energy conservation, water conservation and building site conservation. Sustainable building standards and code, such as the International Green Construction Code (IgCC) of International Code Council (ICC), comprise rules developed by organizations involved in the development of construction standards. These codes outline the minimum requirements for sustainable building elements such as building materials as well as fittings meant for heating and cooling (Meacham, 2010).

The European Union has divided its sustainable building regulations into five major areas including planning, materials, waste, building assessment, and operational carbon emissions. Reducing operational carbon emissions is the primary driver in construction sustainability in Europe. For example, to achieve this, the UK government has set a target that is binding contractors legally. The target is to have reduced its national emission of greenhouse gases by more than 79% by 2050, with 34% decrease by 2020 as the intermediate target. According to the Energy Performance of Buildings Directive (EPBD), newly constructed buildings will be required to meet the 'nearly zero energy' requirement by December 2020 (David and Aleksander, 2005).

To achieve the zero carbon standards, the UK government has developed a hierarchy of steps. To begin with, Steinberg et al. (2010), argue that there is a great need to make sure that the constructed buildings have a high level of efficiency as far as fabric energy is concerned. Furthermore, the buildings are expected to use efficient lighting, cooling, heating and ventilation systems. Secondly, it is necessary to consider Carbon Compliance required for construction sites or regions near construction sites. The third step in the hierarchy is thinking of allowable solutions important in offsetting 'residual emissions'. Exporting renewable heat or low carbon to neighboring constructions is one of the allowable solutions.

Europe is currently lacking well developed methodologies for use in objective quantification and assessment of the three features of sustainable construction in the form of social, economic and environmental sustainability (Langston & Ding, 2010). However, some procedures and tools are accepted for use in the assessment of the environmental effects of buildings and construction activities. BREEAM is the assessment tool commonly used in the UK as well as other parts of the world such as Norway where it is known as BREEAM-NOR. One of its aims is to mitigate the impacts of buildings' life cycle on the environment. Additionally, it makes sure that the recognition of the buildings' level of sustainability is based on their benefits to the environment. The tool is very important to European governments as it provides a reliable label for buildings based on their sustainability. It is through this tool that the demand for sustainable buildings is stimulated (McDonough & Braungart, 2013).

Regulations have been developed in Europe to prevent the pollution of the environment by waste produced during construction activities. Article 40 of the Waste Framework Directive requires EU members to enforce laws, administrative provisions and regulations to reduce the effect of construction waste on the environment. For example, the UK challenges its citizens to work hard towards achievement of the target to reuse and recycle at least 70% of its total demolition and construction waste before 2020. To achieve this, a five-step hierarchy will need to be considered, including waste prevention, reuse, recycling, recovery, and safe disposal. Prevention requires the citizens to use less hazardous construction materials and keep them for longer periods (Dator, 2010). As far as construction materials are concerned, Europe has a 'Green Guide' for designers. This guides them on how to select appropriate construction materials and components. For this guide, it is a good idea to complement the best sustainable projects with some kind of financial help from the administration or the government. Carbon foot- printing is also being used in the UK's construction industry to allow the building designers to

select the construction materials associated with low carbon emission. The materials used in the UK construction industry are expected to be obtained through sustainable methods and from sustainable sources as guided by the responsible sourcing in BREEAM 2014. The planning system in the UK has an important role to play in the delivery of sustainable development. It is meant to ensure that buildings are constructed in a manner that guarantees economic, social and environmental sustainability (O´Neill & Gibbs, 2014).

Spain also has moved towards more sustainable regulations with the adaptation of the European directives thorough the Royal Decree 1027/2007, which approved the Regulation of Thermal Installations in Buildings (RITE –Reglamento de Instalaciones Térmicas en los Edificios). This controls hot sanitary water and heating systems in buildings in order to reach a good comfort level and an optimal energy usage (Martínez et al. 2011). Moreover, the Royal Decree 1675/2008, with Spanish Technical Building Code (CTE – Código Técnico de Edificación) also came into force to promote sustainable building (Martínez et al. 2011).

In addition, the Spanish national renewable energies plan of action (Plan de Acción Nacional de Energías Renovables de España, PANER) governs legislation on photovoltaic (PVs) power generation, stating to follow EU Directive 2009/28/EC. Up to the year 2020, this directive requires a 20% share of renewable sources in the total energy consumption. However, Spain adopted legislation to foster solar PVs as well as other environmentally friendly power generation significantly earlier to this directive. Additionally, The Royal Decree 661/2007, which replaced the Royal Decree 436/2004 allowed generation facilities based on renewable energies to sell their energy surplus to distributors in the Spanish energy market.

Ireland has also moved towards sustainable practices through the enforcement of

regulations on waste management and energy efficiency. For example, based on the EU Directive 92/75/EEC on Energy Labelling of Household Appliances, householders reduce energy use by buying energy-efficient appliances thus reducing greenhouse gas emissions nationwide. Ireland has also applied the 2001 directive on the Promotion of Electricity Produced from Renewable Energy Sources (RES-E-Directive) which aims to achieve a major increase in renewable generated electricity within the EU state members. Ireland's target was to ensure that 13.2% of all electricity generated in 2010 was from renewable sources.

3.4. Regulations for green construction management

Over the world, it is expected that the individuals involved in the construction process will make an effort to understand which sections of the environment are most vulnerable to the impact of construction activities. Assessments are often carried out to understand environmental effect in both the construction site and the neighbouring areas. The initial assessment of the site is, therefore, important as it allows the people involved in the construction process to identify areas that require protection. When environmental regulations are in place, construction companies and clients are required to protect sensitive fauna and flora as well as aquatic animals and plants in cases where water bodies are affected by the construction activities (Bon-Gang & See, 2012). The assessment should also include the possible impact of vibrations, noise and air discharges on the lives of nearby residents if the construction site is located near hospitals, schools or residential areas.

Various nations such as the USA, South Africa and Singapore have different forms of regulations requiring people involved in construction projects to conduct risk assessments. For example, the Obama administration has committed itself to reduce environmental risks in the construction industry by setting aside billions of dollars for

this purpose. The initiative was contained in the American Recovery and Reinvestment Act of 2009. The law resulting from this act supported the funding of various state energy programs, home weatherization programs, green schools and green building training. In addition to funding, the US government has provided regulations dealing with best practice in risk minimization for green construction. This involves identification and ranking of all risks possible in the course of developing a specific project. The first step in the risk assessment process is collection of relevant information to aid in the assessment process. Hazard identification should involve specification of activities that may adversely affect human health or the environment in general. Hazards with the potential to cause noise, land, air and water pollution are identified and previous experience is used to analyze the likelihood of a risk being caused by a certain hazard.

In the United States, the efforts to come up with a green building industry are spearheaded by the U.S Green Building Council (USGBC) (Howard, 2014). Additionally, ENERGY STAR together with the U.S Department of Energy and the U.S Environmental Protection Agency guide businesses on how to come up with strategic approaches to energy management as part of their green building initiative. In fact, LEED was developed by USGBC to act as the rating system for buildings in the U.S (Turner & Frankel, 2008). Its main objectives are improving energy efficiency, energy performance benchmarking and evaluating and implementing renewable energy strategies. At the same time, it is expected that awareness and educational programs are developed and managed.

Singapore is the leading nation on the management and regulation of green building initiatives in Asia. This can be seen through the Singapore Green Building Council actions in the country. The council is dedicated to a provision of resource efficiency management, reduction of carbon footprint, promotion of environmental stewardship as

well as reduction of waste and environmental pollution.

In Africa, South Africa has been the role model for other nations through the efforts it has made to meet the green building standards developed by the World Green Building Council (WGBC). This has been spearheaded by the Green Building Council of South Africa (GBCSA), which is an official member of WGBC. This council provides relevant information about green building and provides the criteria for use when rating whether a project is 'green' or not. Furthermore, it is aimed at providing training and accreditation in an effort to make sure that professionals in the building industry are aware of sound ways to make the world greener.

In Europe, the Construction Design and Management regulations (CDM regulations) are used as a legal guide for people working in construction. Through the regulations that came into force in 2007, designers, contractors and clients have specific roles towards the achievement of a healthy and safe construction environment. These regulations are to be followed for the entire lifetime of the construction, from the project inception to its demolition. According to these regulations, 'notifiable' projects are those lasting for more than 30 days or taking longer than 500-person-day. In such projects, a CDM coordinator and a skilled principle contractor are appointed to notify the Health and Safety Executive (HSE).

The EU requires designers to get rid of hazards in addition to reducing risks, and should do this to any possible practical extent. With regard to land disturbance and associated consequences, prevention should be thought of before treatment measures. The EU requires the parties involved to prevent noise pollution as much as possible with measures such as reducing the number of times noisy equipment is operated to reduce noise pollution, especially where the construction site is located near residential areas (Wedding, 2008). It is also required that site management team keeps a document to

justify the need for out-of-hours work. Additionally, people affected by these activities must be notified as early as possible. To make sure that the discharge of waste into the environment is reduced, countries in the EU require parties involved in a construction project to conduct an assessment aimed at waste minimization (Dator, 2010). The assessment should examine the opportunities for waste recycling, reuse, reduction and avoidance. Waste reduction initiatives should be selected in their right order of preference, starting with waste avoidance, followed by reduction, reuse, and finally waste recycling.

3.5. Outstanding sustainable construction projects

There are various construction projects in the world that have been developed using sustainable materials and techniques. Before a project is declared sustainable, various aspects of its building process are assessed including how the project is managed in terms of sustainability, the building input, quality of the indoor environment, building materials, energy and water consumption, level of innovation and the environmental impact. The level of innovation, carbon emissions and the way land is used are also considered.

A great example of a sustainable project is the Herman Miller Market Place located in Zeeland Michigan, United States which achieves a great deal of energy savings through the use of standard materials that guarantee sustainable heating, ventilation and air conditioning. The building has an automation system including rooftop units with a high level of efficiency, a great range of energy recovery units for air as well as perimeter radiant heating. The design of this building allows for abundant daylight decreasing the energy required for indoor lighting. To achieve this, the designers ensured that over 62% of its exterior wall was made of glass. In addition to the efficient use of materials and saving a great deal of energy, the Herman Miller MarketPlace design is socially

sustainable. The development of this project condensed resources and moved workers from four diverse buildings into a single market place building. Furthermore, more than half of the waste generated by the construction activities was recycled and the remaining waste was placed in a landfill in an ecologically friendly manner. The general contractor of the project, Triangle Associates, used a construction waste management plan that required various disposal bins for general refuse, cardboard, scrap metal, concrete and wood.

The crushed concrete and concrete rebar used in the project development were fully post-consumer recycled. The contractor used 90% post-consumer structural steel and 95% post-consumer recycled roof deck, floor deck and metal joists. When developing the project, the contractor was aware that the use of wood for formwork is associated with poor forest management practices and that this wood was landfilled (Hui, 2010).

In respect of best energy savings, Beddington Zero Energy Development (BedZED) is one of the most remarkable sustainable projects in the world. As the largest eco-village in the UK, it has commercial workspaces, 18 work/live units, 82 residential homes and a number of on-site facilities. The village is located in Hackbridge region of London City, England. This project met the economical sustainability at its early stages as the land for the construction site was bought from the local authority at a lower price than the market value (Langston and Ding, 2010). Since the project encourages low-energy-emission, cars are discouraged from the housing. The project's transport authorities encourage walking, cycling and public transport, with a small parking space. This reduces noise pollution and air pollution to become environmentally sustainable. Its sustainability is increased by the fact that it is located near bus and rail links. In its zero energy concept, BedZED's energy sources are all renewable and onsite. The project has a total of 777 square meters of solar panels. To meet the energy efficiency requirement for a sustainable construction, the houses were designed to face south for solar gain.

Additionally, the houses are characterized by high thermal insulation and triple glazing. The design also provided for most rainwater being harvested and reused. Appliances used are water-efficient, with recycled water being used whenever possible. In addition, materials were obtained from renewable sources and facilities provided for recycling.

A further example of sustainability is the King Abdullah University of Science and Technology (KAUST) located in Thuwal, a short distance from Jeddah, Saudi Arabia. In fact, the university has been recognized to be among of the top 10 winners of the American Institute of Architects green building awards. It is important to note that implementation of strategies to save energy in Saudi Arabia is not economically feasible due to the low cost of electricity in this nation, a condition associated with a great deal of government subsidies (Nimah, 2013). This means that the electricity end-users would not obtain an economy as far as the subsidy is in operation. However, strategies to save energy were considered in the KAUST's design to make it a good example of green buildings in Saudi Arabia despite the financial return.

A 2 MW PVs system was installed on the roof of one of the University's main academic campus buildings. The solar power plant, with 9,300 high efficiency solar panels (provided by SunPower™), is the largest PV installation in Saudi Arabia to date. The high-efficiency solar modules were selected as the ideal solution to make the best use of the available space resulting in a high energy production per square meter (SunPower, 2016). According to same source, the actual yield of the system is almost 5% higher than planned with annual energy production of more than 3,000 MW, which is used to power the campus facilities. Figures 3.9 shows some sustainability features in KAUST's campus.

Figure 3 . 8: Some Sustainability Features in the KAUST's Campus (HOK, 2016)

Inspired by the traditional architecture of the Middle East, the architects in this project made efforts to respond to the humid and hot climate in the region, which was discussed in chapter one. Therefore, the buildings were built in close proximity to each other in order to make sure that only a small area of the facades is open to the sun to promote passive ventilation between the buildings. The circulation thoroughfares in this university are passively cooled and shaded. Additionally, the social spaces and roofs are designed to provide sufficient natural lighting. The designers were keen to create a campus that discouraged the use of cars and encourage walking as well as alternative systems of transport including buses, community-shared electric vehicles and bicycles (Elgendy, 2015). To protect the mangrove forests and coral reefs surrounding the project from the effects of construction, a 50 meter buffer region was established to limit the construction and development activity within the two marine habitats. Storm water treatment and sediment and run-off capturing with the site water protected the

surrounding ecosystems. Owing to the fact that the sun intensity and heat gain in this region is very high, the designers used paving materials made of light color in order to improve the buildings' solar reflectivity. The cooling techniques applied in this project such as displacement ventilation, heat recovery wheels and chilled beams are low energy techniques. All black and gray water is treated before being used for irrigation to reduce the need for non-potable water. Adaptive plants and native vegetation were also planted on site to reduce the need for irrigation and water demand (Elgendy, 2015).

The design team in KAUST selected building materials that minimized any detrimental environmental effects as follows:

- Local concrete with high levels of recycled content
- Local steel with high levels of recycled content
- Interior finishes with low levels of VOC and high levels of recycled content including gypsum board, carpet tile, ceiling tiles, paints, adhesives, and millwork
- Interior furniture systems that contain no VOC, which are Greenguard Certified and with high levels of recycled content
- All the wood used in campus was purchased from sustainability managed forests and is Forest Stewardship Council (FSC) certified
- 75 percent of all construction waste was recycled for the campus of KAUST

Although this is an outstanding example in Saudi Arabia, the fact is that this project was built by individual efforts in a place where the current building codes, standards, and regulations are not in support of sustainable construction principles and/or practices. Therefore, this research aims to grasp lessons from this local example as well as other examples worldwide.

3.6. Important Requirements for Sustainable Construction in Developing Countries

In developing countries, considering the requirements for sustainable construction can be regarded as merely creating another layer to the existing complex difficulties in construction.

Reffat (2004), argued that sustainability and sustainable construction are not yet an integral part of decision-making and business practices in Middle East and the concept has only recently been introduced to the construction sector. The typical perception is that the presentation of sustainable construction practices will increase costs and decrease profit. The need to make additional investments in machinery, equipment and training is very often an excuse not to comply with sustainability principles. The construction industry complains of lack of resources to invest in the technological changes that are required for the application of sustainability and they are concerned about the reduction of their profits. While the costs of the change to more sustainable construction will increase, there are some related savings resulting from efficient resource use, higher productivity and reduced risks. As the potential of savings is seen, this would bring no need for financial premiums (Jones Lang LaSalle Inc., 2013). Miranda and Marulanda (2002), stated that the focus must be on identifying ways of capitalizing on the benefits of sustainability to increase profitability.

Sustainability is not the only responsibility of governments and the construction industry but developing countries citizens need to get involved and be aware of the impacts of their behavior and their use and misuse of all types of resources. Developing of campaigns that inform the public with regard to the benefits and opportunities of the use of environmentally friendly building materials and products is significant while this, on the other hand, encourages a change in consumer habits towards the use of resources in more sustainable manner (Reffat, 2004). However, a general interest is essential in the

issue of sustainability by the construction sector, its stakeholders and clients. Du Plessis (2002), indicated that sustainability should be propagated differently through the various stakeholders. These indications include that politicians should include sustainability issues actively in their political agendas; the manufacturers should include more environmental measures in materials or product specifications; the local authorities should adopt sustainability principles or drive requirements for plan approvals, land use or land sub-division; the built environment professionals should consider sustainability in the brief, design criteria or specifications; and relevant training institutions need to focus on sustainability.

The lack of coordination to manage resources in a more efficient way is a primary problem in developing countries. Uniting resources from different organizations, in fact, could help to increase the impact of these resources. According to Reffat (2004), *"Working together, the financing of research and educational activities, as well as the responsibilities to develop the construction sector can be shared by all parties."* Likewise, costs can be significantly reduced if the construction sector works together and shares responsibilities with government, universities and other private sectors.

It is a fact that defects and inefficient processes are expensive and waste environmental resources as well as posing dangers to construction workers and end-users (Reffat 2004). The bad performance of construction products also reduces the life's quality of users. According to the same source, improving the quality of construction products and the efficiency and safety of the construction process are some of the most important steps towards more sustainable construction and it is a priority for the construction sector to reduce the use of natural resources.

According to Du Plessis (2002), areas to improve the quality of construction processes and products include the reduction of building material wastage, the increase in the use

of recycled waste as building materials, energy efficiency in buildings, water conservation, durability and maintenance, and innovation in building materials and methods.

3.7. Sustainability in the Middle East and the Saudi Arabian Building Sector

Sustainability, in general, includes a blend of environmental, economic and social responsibilities. In the Middle East, there has been considerable interest in recent years with regard to the concept of sustainable construction. The main drivers behind promoting sustainability are ecological and energy considerations together with some other factors such as health-related concerns and the desire to improve the quality of resident's life. Sustainable buildings, in theory, relate to the notion of climate-responsive design. This gives an importance to natural energy sources and systems with the aim of achieving building comfort through interactions between the dynamic conditions of the building's environment (Hyde, 2000).

However, sustainable principles are absent in current Saudi buildings in terms of green construction and project management. Construction industry stakeholders are focusing on time and cost issues rather than on the environmental impact and overall quality of construction. This, in turn, has led to the absence of sustainability principles in the industry and in the minds of most decision makes. It is a fact that there are no regulations, or compulsory building codes that incorporate the principles of sustainable construction in Saudi Arabia. Taleb and Sharples (2011), indicated that it has been argued by many scholars that the application of a rational set of sustainable construction codes and standards is one of the most vital and cost-effective ways to promote widespread sustainable construction practices. Such building codes have been widely adopted in developed nations, and more recently in countries such as China, Taiwan, and Argentina after the energy crises of the 1990s. However, it appears that the

sustainable building regulations in some of the countries of the European Union are amongst the most stringent and should be followed by developing nations.

Unlike traditional building materials and techniques that were built as a response to local climate, many current construction materials lack sustainability. No sustainable materials or construction methods are currently available in the market of Saudi Arabia for example. In fact, there is a strong dependence on modern materials that ignores these negative impacts on the environment.

Regarding energy, current Saudi buildings are dependent on air conditioning that consumes massive amounts of electricity. As a result of poorly designed buildings in the Gulf Cooperation Council countries (GCC), which include Saudi Arabia, nearly 80% of household electricity is used for air conditioning and refrigeration purposes (Akbari, 1996). According to Al-Shehri (2008), the rapid population growth and the increased urbanization in Saudi Arabia caused not only the residential sector booming, but also constituted more than half of the country's energy demand.

The design of modern constructions in Saudi Arabia is no longer based on the principles of vernacular architecture. Vernacular architecture used local building resources and passive and low-energy strategies that could lead to reducing the need for both air conditioning and lighting requirements (Al-ismaily, 1997). Unfortunately, the electricity generation in Saudi Arabia is completely dependent on the unsustainable practice of burning fossil fuels that causes major environmental impacts on air, climate, water and land (Alnatheer, 2006). Additionally, the use of sustainable energy technologies such as solar photovoltaic is rare in Saudi Arabia despite the abundant availability of renewable energy sources (Al-Saleh, 2009) (Taleb and Pitts, 2006). In Morocco, for example, certain facilities are providing about 580 MW of electricity from solar PVs in which is enough to power a million homes in the city of Ouarzazate (the Guardian, 2015).

With regards to water, Saudi Arabia is one of the driest regions in the world with no permanent rivers or lakes. Figure 3.10 shows the map of annual rainfall in Saudi Arabia. Thus, the country depends heavily on desalination plants to bring water supplies to the population scattered across the country. In fact, the development of 33 desalination plants made Saudi Arabia the world's largest producer of desalinated water (Vincent, 2008). Desalination plants are great energy consumers, however, the adoption of solar PVs could reduce the energy costs in the operation of desalination plants.

Additionally, the low prices of water and electricity provide no incentive for water and energy conservation in Saudi Arabia. Furthermore, the design of Saudi houses tends to lay on a luxurious style of living with no regard to any sustainability principles. For example, Saudi houses tend to be large residences when compared to other parts of the world, with air conditioning units running continuously. Consequently, there is an overwhelming need to improve the efficiency of energy use and water consumption in Saudi constructions through the application of sustainable principles. Contemporary studies indicate that having plentiful oil reserves, heavily subsided electricity and water prices generates an absence of awareness with regard to environmental concerns as well as a lack of regulations and policies in terms of sustainable construction implementation. In fact, these factors are among the most substantial barriers to an effective sustainability in the country (Al-Yami and Price, 2006) (Taleb and Sharples, 2011).

From the above, it is obvious that Saudi buildings pose a strong impact on the environment. Furthermore, natural resources are in danger due to the excessive use of materials resources and the lack of waste management solutions.

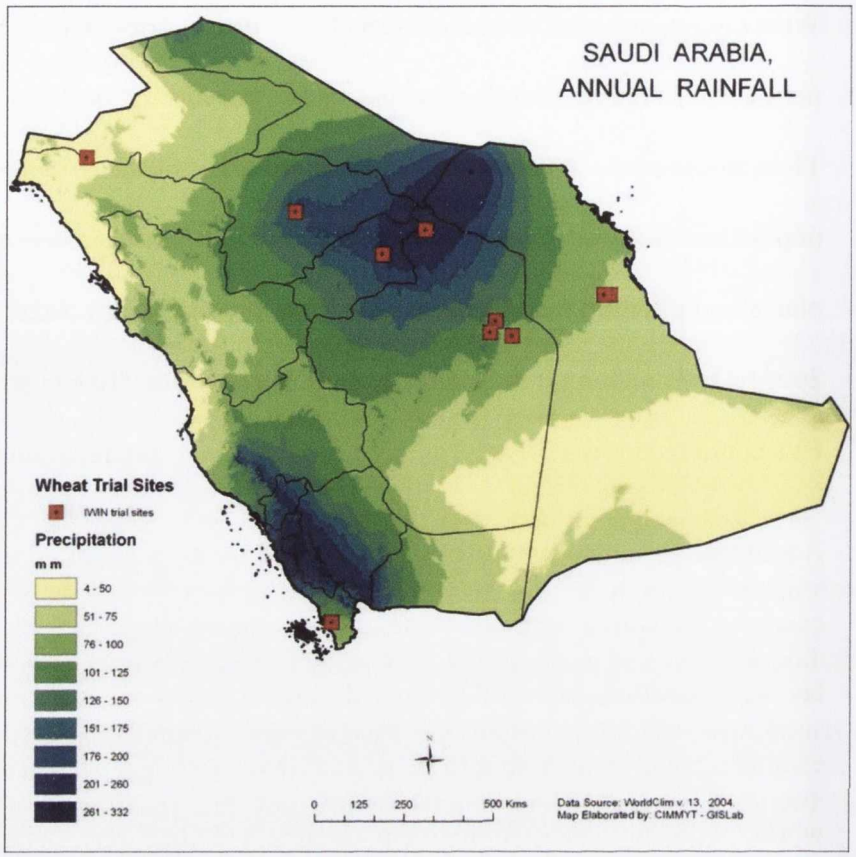


Figure 3 . 9: Map of annual rainfall in Saudi Arabia

(www.old.wheatatlas.org)

3.8. Green Construction in Saudi Arabia and Mecca

According to Faisal Al-Fadl, Secretary General of the Saudi Green Building Forum, the investment in environmentally friendly building projects in Saudi Arabia is set to reach over $26 billions. Among 1,350 projects that are based in the Middle East, Saudi Arabia is home to 5 percent of the Middle East green building projects (Al-Fadl, Saudi Gazette, 2014).

According to The Green Building Information Gateway (GBIG), a product of the U.S. Green Building Council, there are 46 Buildings in Saudi Arabia with green activities. In addition, 988 are the total number of green activities (including some construction projects) in the Kingdom. Among this, only 4 activities are LEED certified with total area of about 750000 square meters. Examples of these activities are KAUST and King

Abdullah Financial District in Riyadh. As aforementioned, this earned the highest LEED Platinum certification (ASHRAE Journal, 2012), and was also named as one of the winners of the American Institute of Architects' Top 10 Green Buildings awards for 2010. KAUST, completed in September 2009, is an international graduate-level research university established by the government-owned company Aramco, the world's largest energy corporation. The aim of this project was to drive innovation in science and technology and to support world-class research in areas such as energy and the environment. Traditional inspiration led KAUST's architects to respond to the local climate using local elements and considerations. These are some of the elements discussed in chapter one that feature in the compact planning of the traditional Arab cities; the traditional Souk or Market, the overhanging Arabic Bedouin tent, the traditional passive ventilation strategies of the traditional Arabic houses, and the traditional Mashrabiya. In fact, applying some of these historical building's elements is essential to make constructions climatically responsive to local conditions. KAUST has benefited from these techniques and materials. It has become a local example of sustainability in the country as well as in the world due to the application of traditional Saudi Arabian construction methods into modern construction.

Another example of green constructions is the King Abdullah Financial District (KAFD), which was designed to achieve LEED accreditation for all its buildings and became the world's largest green development project and the first LEED-certified district worldwide according to the MEED's Saudi Green Buildings Forum (2011). According to Henning Larsen Architects (the design firm of the project), some sustainable features were taken into consideration during design and construction of the KAFD. These are as follows:

- *"Facades are varied in respect to orientation in order to enhance energy saving.*
- *Local materials reduce energy consumption for transportation.*

- *Quality materials have a long lifetime and require a minimum of maintenance.*
- *Solar cells placed on roofs and integrated into the facades.*
- *Transparency of facades designed to create the best indoor environment controlling heat from the sun and daylight.*
- *Shading of facades to reduce cooling loads and to lower outdoor temperature.*
- *Use of roofscapes to achieve sustainable objectives.*
- *Intelligent lighting reduces energy consumption."*

However, according to GBIG, Mecca has only two projects that are registered but not certified for LEED Certification: Abraj Kudai (registered for LEED Certification on 04/24/2013- project size of 929030 sq. m.) and Makkah Hotel and Commercial Complex, which is registered for LEED Certification on 09/02/2013 with total project size of approximately 176515 square meters.

While there are a number of sustainable developments in the country, there are also many examples of disorganized efforts toward sustainability. In fact, all these projects were built under no green construction codes, specifications or regulation lead by the government or any organization. Therefore, sustainable practices in Saudi Arabia need more careful attention. The benefits of old and current green technologies should be studied and applied to Saudi conditions. Questionnaire and interviews findings in this research suggested some elements and demonstrated their urgent need for application in the construction industry (Chapter 5).

Chapter Four: Research Methodology

4.1. Overview

Green construction practices in the world have been reviewed as well as the history of Saudi construction considering sustainability factors. A survey questionnaire and semi-structured interviews were also used. The respondents were selected from public and private construction companies and institutions. Respondents held different responsibilities in projects and different job positions. In addition, in-depth interviews provided in-depth opinions and attitudes on key issues in Saudi construction.

The list below summarizes the main procedures used to gather data and material from the different entities:

- Writing formal letters to the authorities to obtain permission to investigate.
- Designing a questionnaire with regard to sustainable construction in Saudi Arabia.
- Designing semi-structured interviews for decision makers and authorities in Saudi construction.
- Identifying a correct sample population to be targeted.
- Analysis of the collected data.

The findings of the questionnaire and interviews as well as the literature review allowed the understanding of what sustainable areas or practices should be prioritized in the research. These identified a number of construction areas, which need to change toward sustainability. As a result, the research focused in three areas including solar energy, sustainable construction materials and building insulation. In addition, a typical residential building was selected as a case study to which the sustainable solutions above were applied, and calculations and simulations undertaken using a simulation software program known as Integrated Environmental Solutions – Virtual Environment software. This was chosen amongst others to measure and evaluate the benefits of the proposed sustainable solutions.

This study employs a combination of primary and secondary research methods. Primary research includes questionnaire surveys and interviews. Construction managers and construction decision makers of medium to large sized construction firms along with governmental and academic entities were interviewed regarding specific areas of sustainable construction practices and regulations. Additionally, secondary research gathered specific information in green construction applications, green construction projects, construction growth, economic statistics and other areas. Governmental information, data from private firms that conduct green environmental projects and statistics from large construction firms deemed useful for this study were analyzed.

4.2. Data Collection Tools

Qualitative data were gathered from the review of the literature and the conduct of semi-structured interviews and questionnaires while quantitative data were mainly provided by the IES - Virtual Environment Software and the specific information gathered from green construction applications, construction growth and statistics. As aforementioned, data collection tools included questionnaire surveys and personal interviews.

4.2.1. Questionnaire Design and Structure

According to Yin (1994), using a questionnaire survey is appropriate as a research plan if this research is to be focused on contemporary actions. The questionnaire technique is a widespread and easy method for collecting significant amounts of data in a relatively short time at low cost. However, the lack of details provided by the respondents could be a disadvantage and, according to Creswell (2009), respondents may not freely express their views and attitudes towards the questions in questionnaires. Questionnaires were distributed to construction workforces from different backgrounds in the industry to collect and capture different aspects which were designed following background research and the literature review. The semi-structured questionnaire format was used due to the need of having both open and close-ended questions. Respondents need to be

given the freedom to express themselves and their ideas using open-ended questions since these help exploring issues that a researcher may be unaware of. On the other hand, closed-ended questions are needed to guide the respondents to specific issues (Frazer and Lawley, 2000).

Frazer and Lawley (2000), were given much consideration when designing the questionnaire. They considered five major processes in questionnaire design including to determine the required data based on the main research purposes; to administer the questionnaire length; prepare the draft questionnaire, pre-test and revise the questionnaire to avoid any mistakes and to assess the questionnaire's reliability and validity. The research questionnaire (included in appendix A) consists of six sections as described below.

4.2.1.1. Section One: Personal and Work Experience

This section includes the respondent's name, age, work position and affiliation, which is confidential. Additionally, respondents are asked about the number of years of experience in the construction field.

4.2.1.2. Section Two: General Green Construction Practices

This section focused in general green construction practices in Saudi Arabia to find any sustainable components that may be later used to concentrate the research. It covered the following subjects:

- Types of green building regulations that are currently in practice.
- Current and past applications of any green techniques or methods.
- Willingness to apply green techniques or methods in future.
- Importance of sustainable construction and green building regulations in the future of Saudi Arabia.
- Reasons behind the lack of green building applications and future plans.

4.2.1.3. Section Three: Construction and Project Management

This gathers information on construction and project management areas that can determine sustainability including:

- Level of sustainable construction experience that a consultant/project manager should have in order to execute a new green construction.
- Application of green building assessment methods.
- Improvement of sustainability on-site.
- Considerations to be taken in the bidding process in order to encourage sustainability.
- Team selection for sustainability in construction.
- External stakeholder involvement in pre-project implementations.

4.2.1.4. Section Four: Materials

This section intends to determine the main materials currently used in Saudi construction and gather information on sustainable building materials used in projects. The effect of material cost in green construction is also investigated as well as the willingness to use green techniques, methods and components, and the potential governmental subsidy for green products.

4.2.1.5. Section Five: Energy and Water

This gathers data on key sustainable areas related to Government subsidization of energy prices (possibility of discontinuing subsidy); green energy sources; mandatory regulations to reduce energy consumption; current energy sources and water efficient tools.

4.2.1.6. Section Six: Environment

This refers to the negative impacts that current Saudi buildings have on their surroundings and the use of local plant species and green roofs in construction.

A covering letter accompanied the questionnaire as an introduction (appendix A). The research purpose was indicated in the letter to inform the reader on the overall aim of the study and to encourage a higher rate of response. The letter explained the role of the respondents' answers to the questionnaire and assured the confidentiality of the information provided according to advice by Frankfort-Nachmias and Nachmias (1996).

4.2.2. Pilot Study

The construction of the questionnaire was followed by a pilot study to test its clarity and applicability. This is a standard procedure to test particular research instruments such as a questionnaire or an interview schedule (Teijlingen and Hundley, 2002). Naoum (2007), indicated that a pilot study tests the questionnaire for the wording of the questions and identifies any ambiguous questions, measuring the effectiveness of the standard invitation to respondents. Moreover, it allowed an initial assessment of the participants' understanding, level of difficulty and their willingness to answer sensitive questions (Ghauri, 1995). In order to test the questionnaire five respondents covering different backgrounds (associate professor, civil engineer, construction manager and project managers) answered the following questions (Naoum, 2007):

- *"How long did the questionnaire take to complete?*
- *Were the instructions in the questionnaire clear?*
- *Were any of the questions unclear or ambiguous? If so, identify which ones and why?*
- *Would a respondent object to answer any of the questions? Why?*
- *Has any major topic been omitted?*
- *Is the layout of the questionnaire clear/ attractive?*
- *Any comments or suggestions?"*

According to the results, some changes were made before the final version was distributed.

4.2.3. Covering Letter

A covering letter was written to accompany the distributed questionnaire as an introduction. The research purpose was indicated in the letter to inform the reader as well as to encourage a higher rate of response.

The covering letter included the identity of the sponsoring organization, and the person carrying out the research. It also explained the significant role of the respondents' answers and finally assured the respondents of the confidentiality of the answers provided.

A copy of the final questionnaire and the covering letter are included in appendix A.

4.2.4. Semi-Structured Personal Interviews

These were conducted following the questionnaire distribution. Forty-five highly experienced construction professionals from the Saudi construction industry were interviewed to gather perspectives and perceptions toward sustainable construction. As aforementioned, the semi-structured interview was considered as the most suitable type for data collection as it contains open and closed-ended questions that provide the freedom to investigate particular areas simultaneously allowing to raise specific queries. The characteristics of the semi-structured interview are described by Merton and Kendal (1946), as follows:

- *The interviewees are recognized to have relevant experience in a specific field.*
- *They refer to situations, which have been analyzed prior to the interview.*
- *They focus on the interviewees' experiences concerning the situation under study.*

According to Patton (2002) and Sekaran (1992), this technique helps explore and discuss the research issues in detail based on direct quotations from the interviewees' experience, knowledge and background. The semi-structured interviews focused on current Saudi sustainable construction applications, challenges facing green construction, future

regulations and best practices to increase sustainability. Quotations and statements that reflect the interviewees' opinions and experience regarding the current and future sustainable practice and regulations were also gathered. The interviews included the following questions (appendix B).

1. What challenges face the current Saudi sustainable construction?
2. What are the threats toward Saudi construction and the environment due to the lack of sustainability?
3. What sustainable legislation/guidelines/standards are required relating construction and project management?
4. What sustainable legislation/guidelines/standards are required on building materials?
5. What sustainable legislation/guidelines/standards are required on energy and water?
6. What sustainable legislation/guidelines/standards are required with regard to the environment?

4.3. Case Study and Simulation Software

A typical residential building was selected for the application of sustainable elements. Details of the case study building and the methods used to apply sustainability are discussed in later chapters. A 3D model of the building was made to be used in the software for dynamic simulation. As aforementioned, the simulation software program is the Integrated Environmental Solutions – Virtual Environment (IESVE). Within the software, different tools were used to come up with the optimum outcome. These tools include the use of ModelIT, ApacheSIM, MacroFlo and SunCast.

There are many advantages of using the chosen simulation software to conduct the study objectives. The IESVE software provides the designers with a variety of variables in simulation analysis of construction. In fact, the model works on the geometric

representation, which embodies the building. As an advantage, IESVE software allows interaction with other energy simulation software tools. A building model can be constructed within IESVE using the "ModelIT" module that can be analysed in a variety of ways. The simulation software also incorporates a tool for dynamic thermal simulation of heat transfer processes of buildings that is called the "ApacheSim". The IESVE software tool was tested using the IES ASHRAE 140 and is qualified as a dynamic model in the Chartered Institution of Building Services Engineers (CIBSE) system of classification. Allowing the building optimization to take into account criteria such as comfort and energy, the IESVE software tool provides an environment for the specifying of the building systems. The dynamic tool "ApacheSim" can be dynamically linked to the "MacroFlo" dynamic tool. This is for natural ventilation and HVAC Apache dynamic tool to perform analysis of air leaks as well as for the analysis of natural lighting and shading of the building. In addition, the "SunCast" is a tool for calculating the position of the sun in the sky, track solar breakthrough throughout the building interior and also incorporated to calculate shadows.

Chapter Five: Questionnaire and Semi-Structured Interview Analysis

5.1. Overview

This chapter discusses and analyzes the data of the questionnaires that were distributed to different construction entities (Appendix A). The data collected were analyzed using Microsoft Excel. The collected responses are presented and analyzed with statistics. The total number of questionnaire respondents is 129. The questionnaire included six parts, which were chosen to reflect the research aims and objectives. These are as follows:

- Personal and Work Experience
- General Green Construction Practices
- Construction and Project Management
- Materials
- Energy and Water
- Environment

5.2. Classification of Questionnaire Respondents (Personal and Work Experience)

The respondents belong to three different groups: government, industry and academia. Among these groups, different job positions from top management to site workers were selected in order to reach different backgrounds and thus different views. Among respondents are site managers, site engineers, general operatives, project managers, resident engineers and inspectors of works. Respondents were not all Saudi nationals; there were some from other parts of the world especially the Middle East. Table 5.1 and figure 5.1 show the details of the respondents.

	Work Position	*Job Sector*	*Number of Respondents*
1	Assistant Professor	Academic	5
2	Associate Professor	Academic	4
3	Board Member, Saudi Green Building Council	Private	2
4	Business Development Manager	Private	4
5	CEO/ Architecture	Private	3
6	CEO/ Construction	Private	4
7	Chief Consultant	Government	2
8	Chief Consultant	Private	2
9	Civil Engineer	Government	14
10	Civil Engineer	Private	11
11	Company Owner	Private	3
12	Construction Manger	Private	10
13	Construction Manger	Government	9
14	Construction Professional	Government	5
15	Consultant	Government	3
16	Consultant	Private	4
17	Director of Research and Assessment	Government	3
18	Director of Research and Assessment	Government	5
19	Executive Director/Utility	Private	1
20	Head of Construction Eng. dept.	Government	5
21	Mega Project Department Engineer	Government	1
22	Project Contractor	Private	4
23	Project Manager	Government	5
24	Project Manager	Private	7
25	Quality Administration Manager	Government	4
26	Real Estate Owner	Private	4
27	Research and Development Director	Government	3
28	Research and Development Director	Private	2
Total			**129**

Table 5 . 1: Division of respondents based on work position and job sector

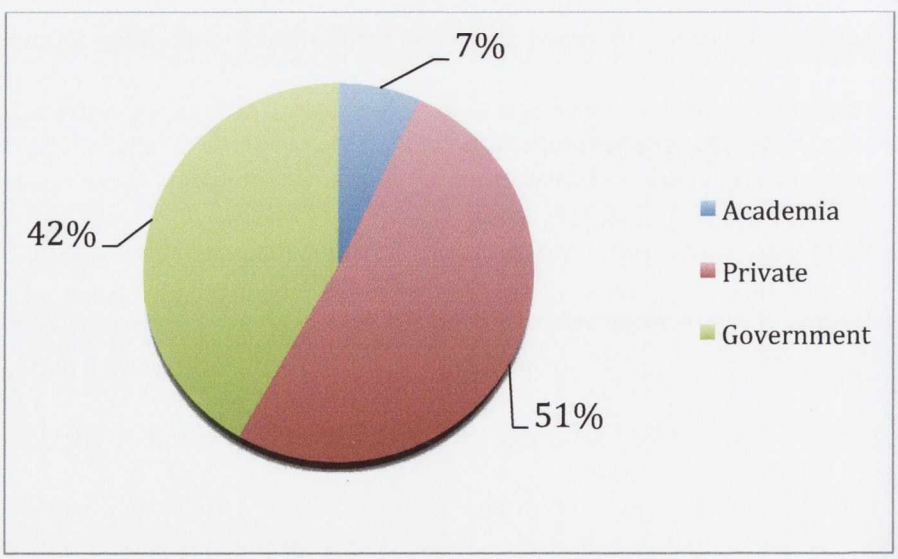


Figure 5 . 1: Percentage of respondents by sector

Figure 5.2 shows the classification of total respondents by their years of experience. 46% of the respondents held over 15 years of experience while 29% of total respondents had between 11 and 15 years of experience and the remaining group are less than 5 years of experience.

	Less than 5 years	5 to 10 years	11 to 15 years	Over 15 years	totals
Number	10	23	37	59	129
Percentage	8%	18%	29%	46%	100%

Figure 5 . 2: Classification of total respondents by their years of experience

5.3. General Green Construction Practice

This part of the questionnaire aims to provide information about current green applications, awareness of sustainability in Saudi Arabian construction and the willingness to apply sustainable construction in the country.

5.3.1. Green building regulations and practices currently in use

92% of respondents indicated that they do not follow any green construction regulations or guidelines since there is no national green construction framework, which they could follow (Table 5.2). The remaining 8% of respondents stated that they follow either regional standards like the United Arab of Emirates (UAE) standards or some international codes when they see the benefit of that to the total work.

Type of Standards	*Respondents Number*	*Percentage*
Regional	4	3%
International	7	5%
None	118	92%
Totals	129	100%

Table 5 . 2: Type of green standards that respondents use

As discussed in Chapter 1, in the past, historic, traditional materials and techniques or elements in Saudi Arabia were developed from sustainable principles. Understanding the past green construction technologies can assist the application of green technologies in future. Figures 5.3 and 5.4 show respondents that have used ancient, traditional sustainable techniques and/or methods (such as sun louvers and rowshans and the willingness to apply more sustainability in future.

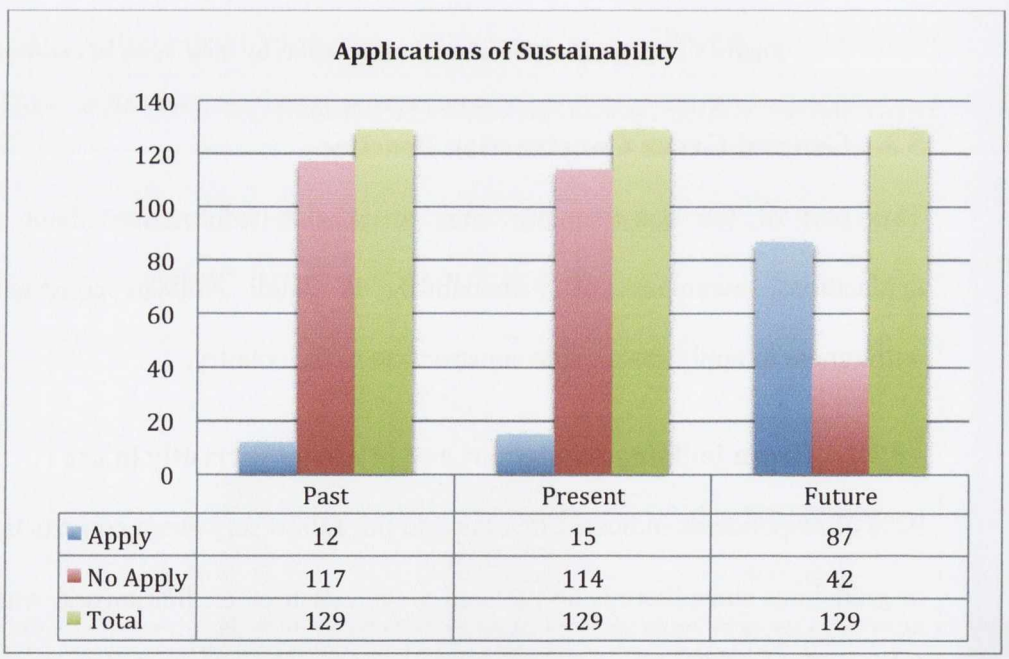


Figure 5 . 3: Application of green construction technologies or methods in past, present, and future

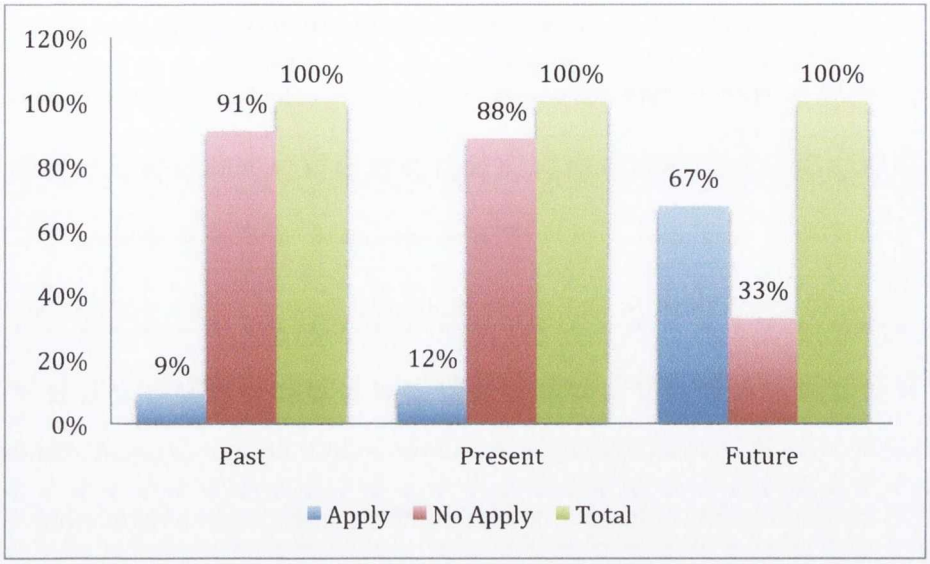
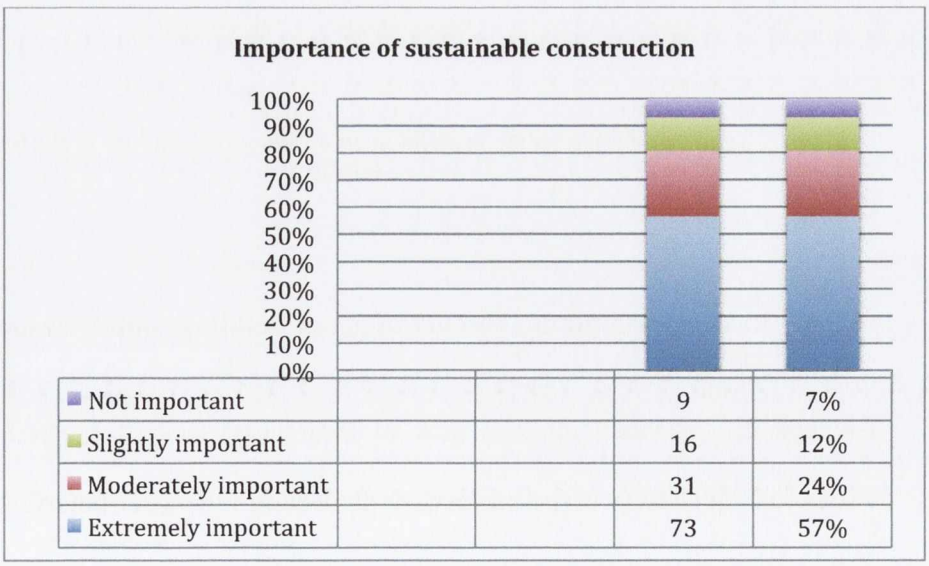


Figure 5 . 4: Percentages of sustainability practices and the willingness of future sustainable applications.

5.3.2. Importance of sustainable construction

57 % of the total respondents believed that it is extremely important to adopt green building regulations or best practice guidelines in the future of the Saudi Arabia while only about 7% do not give it any importance- Figure 5.5.



Not important			9	7%
Slightly important			16	12%
Moderately important			31	24%
Extremely important			73	57%

Figure 5 . 5: Importance of sustainable construction for Saudi Arabia

5.3.3. Application of "Elective" Saudi green building regulations

24% of respondents are willing to apply any elective green buildings regulations in the projects they are involved with while 31% would apply only the minimum green building regulations and 28% would apply these depending on project costs and construction time. In fact, green buildings showed a great potential in terms of economic savings as discussed later in Chapter 7. Approximately 17% showed no intention to apply any green buildings regulations unless the government mandates it. Figure 5.6 summarizes the attitude of the interviewees toward green regulations.

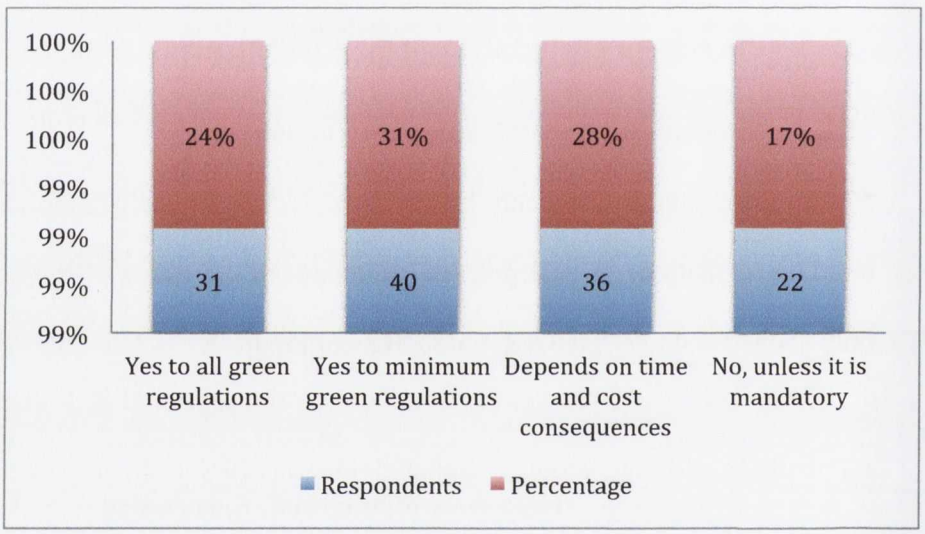


Figure 5 . 6: Attitudes regarding application of buildings regulations in the Saudi construction industry

5.3.4. Reasons behind the absence of green buildings applications in Saudi Arabia

The answers provided include: lack of awareness, lack of green infrastructure and associated high cost, with percentages as showed in Figure 5.7 below.

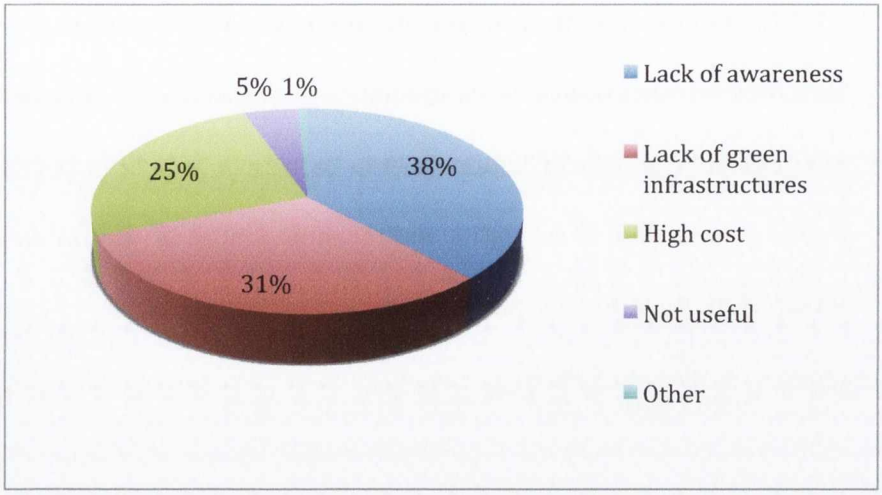


Figure 5 . 7: Reasons behind the absence of green buildings applications

5.3.5. Reasons for the inactivity of the Saudi Green Building Council (SGBC)

SGBC has had no impact toward improving sustainability- Figure 5.8. According to 22% of respondents, this is due to the lack of support from all involved entities in public and private sectors. Some respondents (23%) replied that SGBC is still at foundation stage, although a number of years have passed since its foundation. Others (36%) related the reason behind the current status of SGBC to the general lack of interest and active members. In addition, about 15% linked their answers to the low interest from decision makers while only 4% indicated a lack of motivation to foster sustainability among the persons in charge of the council.

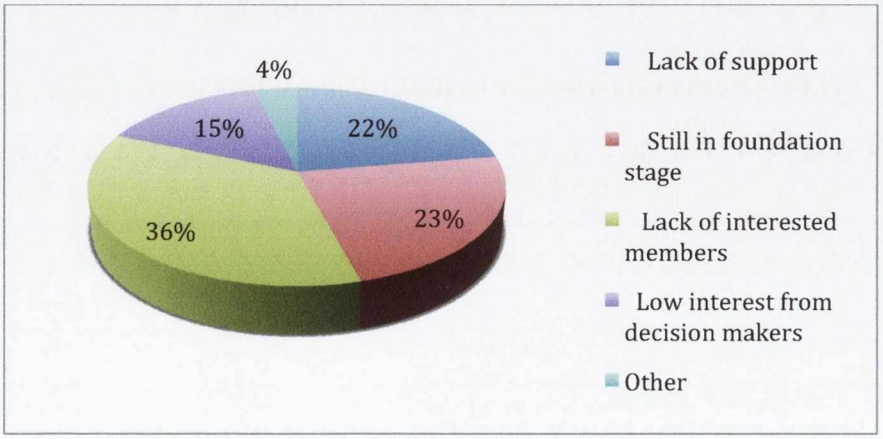


Figure 5 . 8: Reasons behind the SGBC's inactivity

5.3.6. Public awareness of the advantages of sustainability

Respondents were asked if the public is aware of the advantages of sustainability in environmental and social contexts. Approximately 55% of respondents believed that the public is not aware of that while the remaining number (45%) thought that the public is aware of the need for sustainability.

5.4. Construction and Project Management

5.4.1. Importance of previous experience and team selection in green construction

Respondents were asked about the level of green construction experience that a project manager/consultant should have in order for such a project to be constructed sustainably. As shown in Figure 5.9, 82% indicated that a project manager and/or consultant must be a Leadership in Energy and Environmental Design (LEED) accredited professional to best lead sustainable construction. Approximately 14% believed that they must, at least, have experience from previous projects. The remaining minority, 4%, claimed that this is not relevant as there is no need to any green practices.

18% of respondents argued that a number of green construction experts should be hired in team selection process to ensure efficient and sufficient sustainable construction implementation. Some respondents indicated that this should only apply for higher management staff while others believed that green construction expertise should be considered among all levels of construction workers on site.

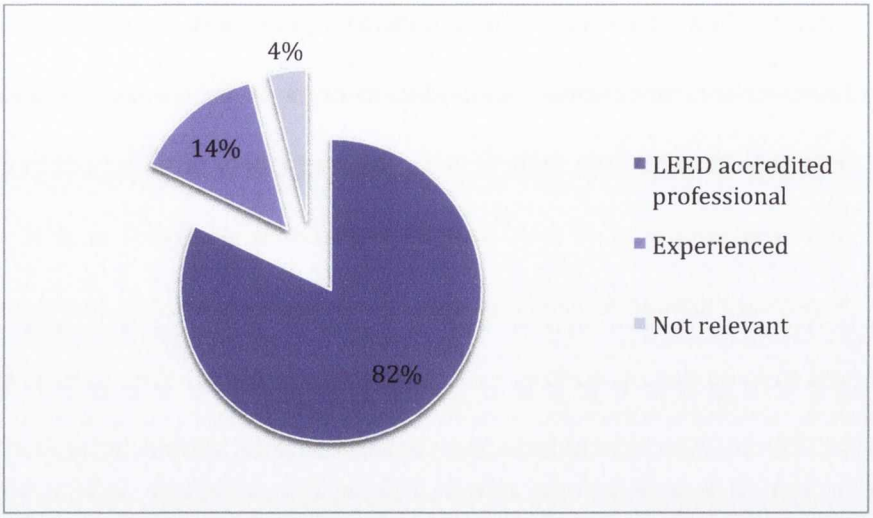


Figure 5 . 9: Types of sustainable experience needed for project managers/consultants

5.4.2. Use of green building assessment methods

Approximately 91% of respondents showed agreement towards the use of green building assessment methods such as LEED or the United Kingdom's Building Research Establishment Environmental Assessment Method (BREEAM) in the Saudi Arabian building sector. They stated that these types of assessments are currently needed however, the remaining percentage (9%) believed the opposite.

5.4.3. Use of sustainable construction practices on site

The respondents proposed the following practices to enhance sustainability on site:

- Considering site characteristics especially mountains and hills slopes in projects, in which, every project needs a proper site investigation and cutting slopes should be designed on the basis of a full geotechnical analysis.
- Considering ecological systems in design and construction processes
- Regulating governmental periodical site inspections to supervise and evaluate sustainable applications.
- Using recyclable materials as well as using recycled materials in new construction.
- Using alternative energies.

5.4.4. Consideration of sustainability in the bidding process as a regulation

Over 85% of respondents state that, in order to encourage sustainability, a lowest-bid cost should not be the main criteria for acceptance during a bidding process; and some other considerations should be put in place such as the capability of a contractor to implement sustainable construction, green projects already completed by the contractor and the number of workers with experience in sustainable construction among the total workforce. The respondents also stated that bids should be invited from pre-qualified contractors.

5.4.5. Involvement of external stakeholders

76% of respondents strongly stated that it is very important to involve external stakeholders such as the local community in projects that may impact them while 24% believed that local involvement is not valuable at the design stage.

5.5. Materials

5.5.1. Materials most used in construction

Most of the respondents indicated that due to economic reasons and the widespread availability; concrete is the most used material in Saudi Arabia. According to most of the respondents, materials made of concrete including bricks, blocks, and tiles are mainly used in their projects. All of respondents indicated the use of materials such as ceramic tiles, glass sheets, steel, aluminum and other alloys. Products based on petrochemicals are also used mostly in doors, windows, sun breakers and sockets. A few respondents use Carbon Fiber Reinforced Polymers (CFRP) in their construction projects to strengthen other materials.

5.5.2. Green buildings materials used at present or in the past

About 12% of respondents indicated that they use some green materials in their current projects. On the other hand, the majority (88%) affirmed their usage of non-green materials. Local concrete, local steel and Portland pozzolan-cement were considered as green due to the fact that they are produced locally and/or with less transport costs and emissions. There are many arguments in this regard as some believe it is green because it is local and the others believe it is not green due to the associated high temperature that is necessary to produce these materials as well as the high amount of carbon emissions produced during the life cycle. More details on this regard were discussed in the literature review. Details of local materials and production can be found in earlier Chapters 1 and 3. In addition, the majority of respondents, in fact, evidenced the lack of green products in the market.

With regard to the high cost of green materials due to their lack of availability, 43% of respondents are willing to use green materials in any future project subject to the long-term benefits to the project and the availability of green materials in the market. However, 57% showed no will to use green materials due to the higher costs associated. In fact, all respondents insisted that if the government subsidizes these materials, they would definitely use them. In addition, approximately half of respondents indicated that the reason behind the high cost of green materials is the lack of a competitive green materials' market in the country.

5.5.3. Application of historic green techniques, elements, methods or materials

Respondents were asked if they would use any historic or traditional green materials or techniques. The majority of the respondents, 84%, argued that the use of historic regional green techniques and materials would help toward achieving sustainability in construction. These components include Rowshans and Mashrabiyas (discussed in the

literature review), use of natural ventilation, and passive designs. In contrast, 16% preferred to disregard the historic and traditional resources.

5.6. Energy and Water

5.6.1. Abolition of government's energy subsidy

The current energy subsidy should be reassigned to sustainable products and materials. 78% of respondents supported this idea to make end-users more responsible regarding energy consumption. However, 22% believed in the continuation of the government energy support.

5.6.2. Green energy sources to support sustainable constructions

The only green energy source that all respondents firmly stated should be used in Saudi Arabia is solar energy. As one of the interviewees stated,*" We are in a place that has been given the strong sun shining almost all around the year. So, we have to use this source of energy in all types of buildings as the fuel may not last long"*. However, a few indicated the need to also use wind power as a sustainable energy source.

5.6.3. Mandatory regulations to enhance low-energy-consumption by building occupiers

Approximately 70% of respondents stated the following as mandatory regulations to reduce energy consumption in Saudi buildings:

- Increasing the electricity bills to encourage rational use of electricity by end-users
- Conducting periodical maintenance for buildings in regard to power savings and consumption levels and then update building systems if needed.
- Applying more building insulation made of green materials

5.6.4. Energy Sources

97% of respondents depend on energy from fuel sources in construction projects and no one has fully depended on solar energy. However, 3% of respondents had mixed power resource, fuel and solar, in construction projects they are involved with- Figure 5.10.

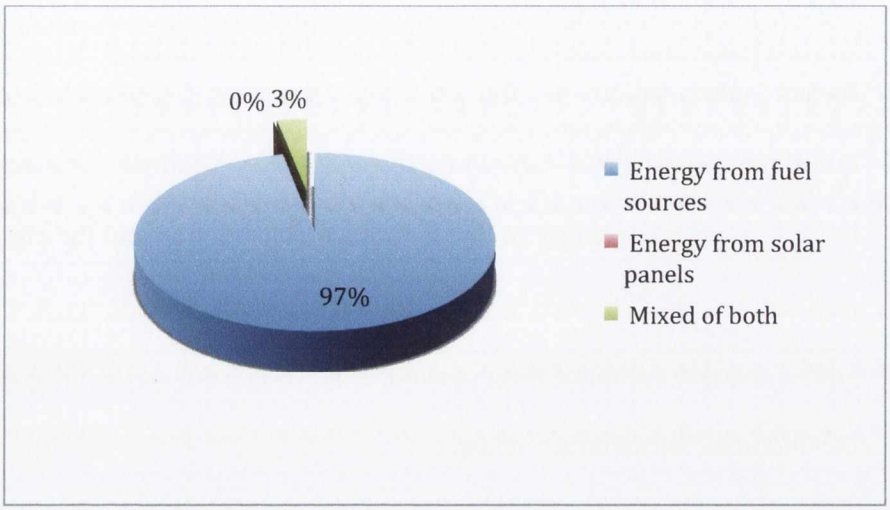


Figure 5 . 10: Sources of energy in construction projects

5.6.5. Adoption of water conservation measures

None of the respondents used any water conservation measures in construction projects. Consequently, the more efficient use of water in current and future building is essential and recommended by more than half of respondents. In fact, one of the biggest problems in the near future will be the lack of water. Everyone should be conscious about it and try to find solutions in order to solve this problem in the future.

5.7. Semi-Structured Interview Analysis

Opinions and attitudes of key construction industry personnel were compiled and analyzed. While the quantitative data from the questionnaire analysis above identified main factors, the qualitative data in these interviews provided a deeper understanding of the current situation in Saudi Arabia with respect to sustainability giving an insight into future regulations and/or best practices according to the interviewees experience, knowledge, understanding and professional status.

5.8. Interviewee's classification

Forty-five experienced professionals of the Saudi construction industry were interviewed (Table 5.1). The selection was based on their expertise in the field of construction, sustainable interest and/or achievements, decision-making nearness and sustainable construction knowledge. In fact, the most experienced ones were selected for further investigation in the personnel interviews (selected from respondents to questionnaire survey in Table 5.1 and Figure 5.2). The main objectives were to identify the status of sustainability in Saudi Arabian construction and the challenges facing their application as well as opinions and attitudes towards developing best practice guidelines and to enhance green building construction. The results of the different areas of focus in the interview are summarized below.

5.9. Reasons behind the lack of sustainable construction in Saudi Arabia

91% of interviewees indicated the lack of green buildings standards and regulations as one of the main challenges to the uptake of sustainable construction in Saudi Arabia; and the need for these as a basis to begin sustainable construction: *"It is obvious that without regulations and standards you cannot move towards sustainability. As you know in USA and Europe, they have green buildings regulations as a basis to start with, which we still do not have"; "Intentions to go more green are not enough, green legislation is needed."*

Other challenges indicated by the interviewees included the bureaucratic rules present in the governmental institutions, the lack of green projects incentives and the lack of competitiveness among construction contractors. Several interviewees also stated that the pre-qualification system and tendering processes need to become more transparent so that the government does not waste any money on over-priced contracts: *"There are no incentives to encourage sustainability like premiums given to green materials,*

products and/or projects. The government and private sector should sit together and rethink the future of the industry." "Competitiveness is an important issue that is not well considered in the construction industry here. For example, there are few construction firms that are usually awarded government projects only because of their size and reputation. Sustainability factors are not considered by the projects owners, especially the government, thus the contractors would never go more green unless they were required."

Some interviewees argued the need for a list of green building construction. They also indicated that a classification of contractors based on green criteria needs consideration by decision makers: *"In my opinion, the classification of contractors should give more attention to sustainability: the greener the company the more points it scores."*

The absence of a sustainable material market is one of the most detrimental factors to the future of sustainability in the country. In fact, this issue was repeated many times by interviewees during the semi-structured interviews. Several quotes reflect this as follows: *"As you may know, the availability of green materials is a key factor to encourage sustainable construction which is absent in the current days." "A foundation for sustainability must include green building regulations as well as knowledge and availability of green building materials and markets." "Local suppliers may not be aware of the benefits of green materials. So, they need to be told about these benefits as they are currently just looking for economic profits."*

The lack of experienced professionals in the Saudi construction industry was also raised; and the fact that experts and experience could be brought from other countries to encourage sustainability: *"Certified green construction professionals should be in charge of any new construction project, especially mid to large projects." "We need individuals who have experience in sustainable construction to be among the construction workforce to better enhance sustainable construction in our country."* The

ignorance of the local environment in construction projects was raised as a further issue detrimental to sustainable construction in Saudi Arabia: *"I can see that one of the reasons behind the lack of sustainable construction in Saudi Arabia is the lack of local construction innovation."*

As a summary, the interviewees understand that sustainable construction in Saudi Arabia faces the following challenges:

- Absence of building contractors' classifications based on green criteria
- Absence of green building regulations and/or standards and guidelines
- Bureaucracy in processing rules
- Ignorance of local environment in construction and the advantages of sustainable materials and construction
- Lack of green construction incentives
- Lack of experts in green construction
- Lack of sustainable materials' suppliers
- Lack of sustainability competitiveness among construction contractors

Some of the above were repeatedly mentioned while others were seldom stated. For instance, most of the interviewees stated that the main challenge that sustainable construction faces in the country is the absence of regulations and standards. Figure 5.11 shows the frequency of these statements. The categories in figures 5.11 to 5.15 are given weights (percentage of number of respondents) by their repetition (number of mentioned times of each category) by respondents.

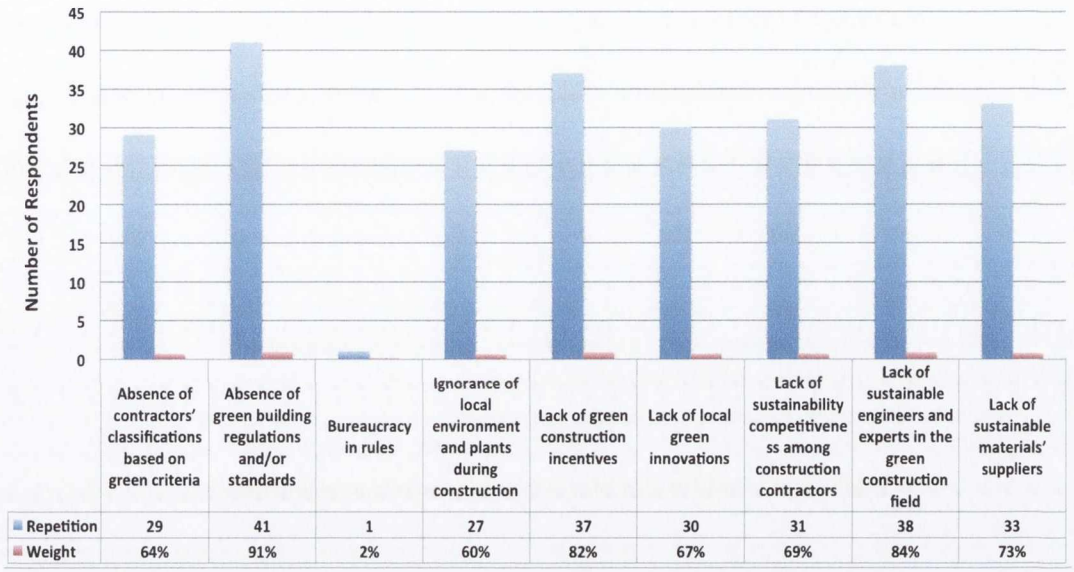


Figure 5 . 11: Challenges facing current sustainable construction application in Saudi Arabia

5.10. Threats due to the lack of sustainability in construction

Threats indicated by interviewees include waste of resources such as energy, water and materials; and the increase of carbon-dioxide emissions. A number of statements reflected this: *"Unfortunately, many decision makers in SA are not aware of the threats to our environment. Resources like energy, materials, and especially the water in the country are endangered. Sustainable construction is the way to encounter these threats."* *"Water, water, water. It is a scarcity in our region and a must be a priority that should be considered in every aspect of our lives including construction."* *"You can imagine the amount of emissions every household and industrial building produces daily. This is a real threat considering our high rate of energy consumption compared to the world average."*

The interviewees also raised the fact that, while some parts of the world are adopting sustainable construction rapidly, current construction practices in Saudi Arabia are behind on sustainability*: "We need to work double time to be able to catch up with the*

rest of the world in sustainability. Lagging behind is what we do not want as we have the most active construction industry in GCC countries and the Middle East."

As a summary of the threats due to the lack of sustainable construction as understood by the interviewees is listed below. Figure 5.12 shows the frequency of these statements.

- Waste of natural resources; water, energy and materials
- Increase in carbon-dioxide emissions
- Saudi Arabia under developed in terms of sustainability

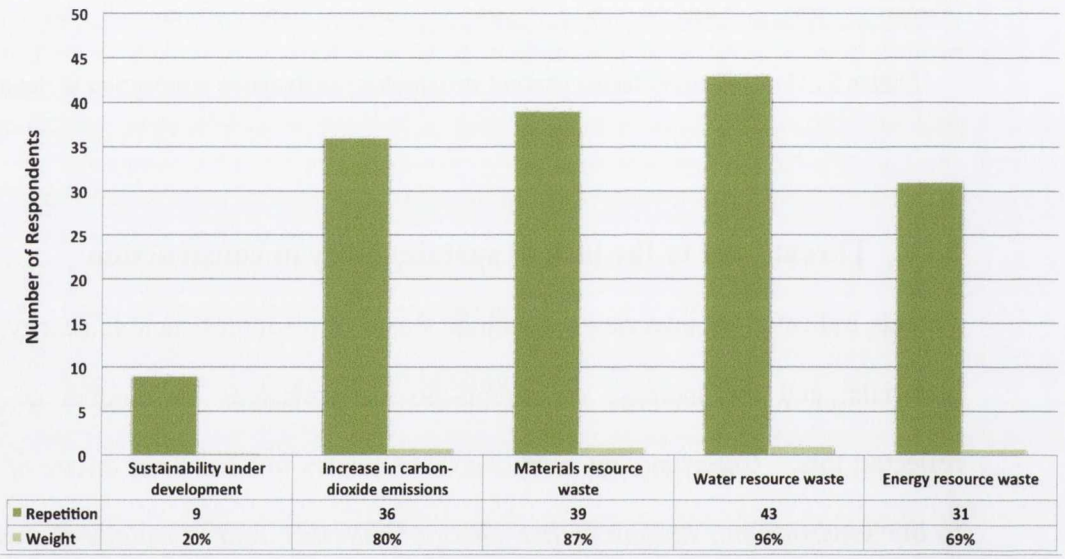


Figure 5 . 12: Threats due to the lack of sustainable constructions

5.11. Green building regulations in construction practices and project management

In order to enhance sustainability in Saudi construction, a sustainability plan should be associated to each new project. Interviewees insisted on this particular issue as a start point to enforce sustainability in construction. This needs to be regulated by the government so that all contractors plan their projects with sustainable goals in mind. As one interviewee said: *"We need to have sustainability in mind during the design stage. Regulating this as mandatory in order to obtain a construction permit would eventually lead to more sustainable construction in a short time."*

It was also clearly stated that more attention should be given to site and environmental disturbance during and after site preparation. Local plants, infills and waste management need to be considered when a project is being implemented: "Current site investigations do not take the environment into consideration. Consequently, regulations are needed in order to reduce the current damage to land and the environment."

Interviewees also argued that sustainable construction experts are essential for the achievement of green construction. Approximately 96% added that green construction professionals should be made mandatory by regulation, especially in medium to large projects: *"experience is needed to better tackle any issue therefore in the construction industry we need experts of sustainable construction to lead new projects." "With no experts in sustainable construction, our hopes of green future would be moving slowly with many mistakes that are avoidable when experts are leading."* Interviewees argued that training for site workers in sustainable construction would be a way to move forward in sustainable construction.

With respect to waste, interviewees put forward recycling in site waste materials as essential to gain sustainability in construction: *"On-site waste material recycling should be a normal process in any construction site. This is a simple way to achieve sustainable goals."* In fact, through experience it is really difficult to make workers aware because, in general, this implies minor economic profits.

In summary, the interviewees understand that adopting the following sustainable practices would be essential to implement sustainability in Saudi Arabia construction (Figure 5.13 shows the frequency of these statements).

- Preparation of sustainability plans as a requirement at design stage
- Avoiding environmental disruption on site

- Hiring sustainable construction professionals to manage projects
- Mandatory training sessions for site workers on sustainable construction
- Mandatory of on-site waste material recycling
- Mandatory use of traditional/local sustainable materials or techniques.

	Avoiding site disturbance	Hiring sustainable construction experts	Mandating bi-monthly or monthly sustainability training sessions	Mandating on-site waste materials recycling	Preparation of sustainability plan report	Using a traditional sustainable element
Repetition	24	43	39	41	37	23
Weight	53%	96%	87%	91%	82%	51%

Figure 5 . 13 Green building proposals in terms of construction and project management

5.12. Green building regulations/practice relating to building materials

Building materials play an important role in sustainable construction. According to 64% of interviewees, law and regulations should consider sustainable local materials such as earth and stones that were used in the past (discussed in Chapter 1) in new construction: *"A percentage of local sustainable materials shall be used in any new construction. This would enforce the use of local materials promoting sustainability."*

Consideration of recycling and the use of recycled materials are essential. Interviewees argued the need to set a range of recycled materials that should be used in projects: *"As you may see, in this site, we have neither recycled nor used recycled materials however, if required by law we would consider it." "Recycled materials should be made available for use in new construction. Recycling materials on site should be compulsory*

as well as the use of the recycled materials in new projects." "Recycling targets should be imposed by law."

More than 80% of interviewees argued that providing guidelines on the toxicity and fire safety of new construction materials (in particular insulation) would be essential; as well as providing guidelines on the availability and application of local sustainable materials which could be included in future guidelines and regulations. A summary of the issues highlighted by the interviewees is as follows (Figure 5.14):

- Avoiding toxic materials
- Providing guidelines on the availability and application of sustainable and local materials for use in projects
- Specifying the amount of local/sustainable and recycled materials that shall be used in new construction
- Making mandatory recycling of materials in construction sites

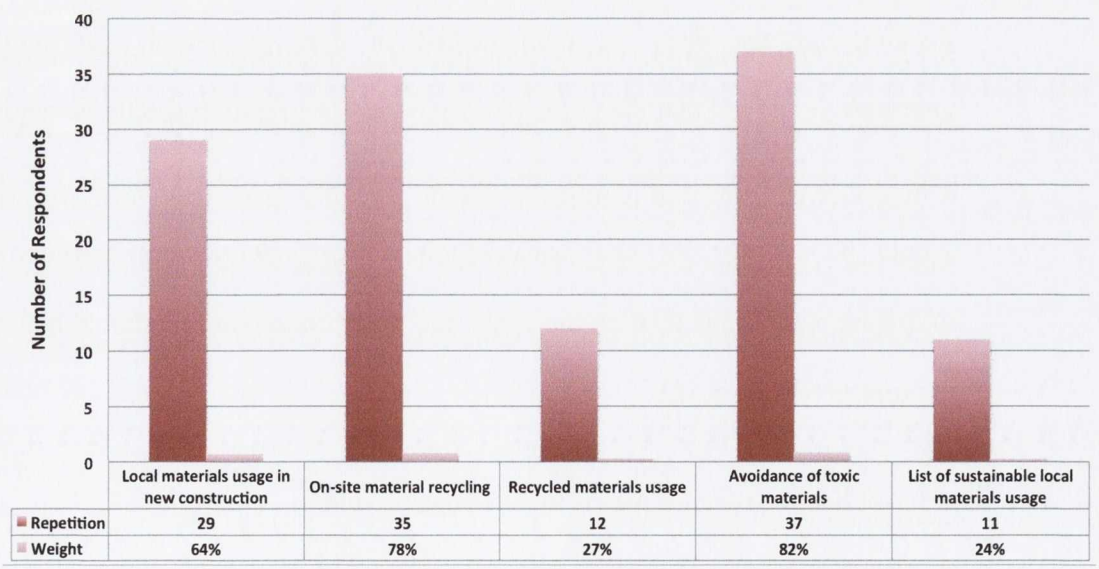


Figure 5 . 14: Green building proposals in terms of sustainable building materials

5.13. Green building regulations/practices relating to energy and water

Most interviewees insisted that each building must have a number of solar panels and that building regulations must indicate the use of solar power as a mandatorily requirement. Additionally, some interviewees stated that the use of wind is essential but not as important as solar power in Saudi Arabia: *"We have sun every day. We need to use this gift from Allah in our new construction so that we do not harm the environment as we already have."*

Thermal insulation is mandatory in Saudi Arabia. Although it is only being implemented in some areas, it was felt by the interviewees that insulation should be applied throughout the whole country: *"Our buildings consume about 80% of the power generated by fuel due to lack of insulation in buildings. All buildings have to be thermally insulated even old buildings need to be renovated."*

With regard to water, most interviewees insisted on measures to lessen the use of water in buildings. According to many interviewees, the use of sustainable water taps and flushing systems must be implemented in new regulations. In addition, most interviewees argued that the reuse of wastewater for irrigation should be required by law and that regulations relating to showerheads, faucets, toilet tanks and leak detection should be adopted for new construction. Most interviewees considered that the following regulations relating to energy and water conservations should be implemented in projects (Figure 5.15):

- Application of solar panels in new construction
- Implementation of means to reuse waste water for irrigation
- Use of sustainable water taps, flushing systems and other water saving features in construction
- Mandatory use of insulation to preserve building energy usage

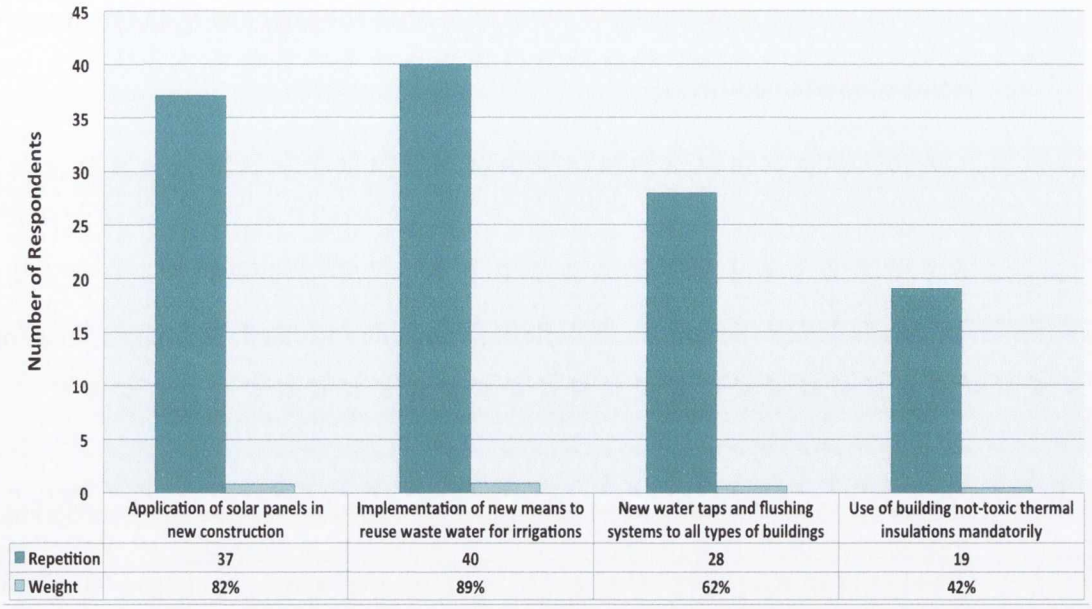


Figure 5 . 15: Green building proposals in terms of energy and water conservation

5.14. Discussion

From the results of the questionnaire, the application of sustainability in construction seems very limited. However, most of the participants seem aware of environmental problems and practices and willing to put them in place if guidelines and regulations were provided and required by law.

The results evidenced the need to focus on sustainable materials. As a result, the research will focus on earth construction, a local sustainable material and construction method traditionally used successfully in the Saudi Arabian climate.

A recurrent pressing issue evidenced by the questionnaires and the interviews (and the fact that the energy consumption rate of Saudis is one of the highest in the world) is the search for sustainable energy sources, essentially solar energy. The results suggested that if sustainable energy would be readily available at a competitive cost, the construction industry would use it. Therefore, the research will focus on the application

of solar photovoltaic panels (PVs) in buildings roofs as one of the main applications to enhance sustainability.

A further recurrent construction challenge with regard to sustainability highlighted in questionnaires and interviews is the need to insulate buildings to save energy, especially in Saudi Arabia where most buildings are not insulated, this seems one of the main concerns of Saudi construction according to the sample population targeted.

There are many aspects of sustainability in construction that need to be studied in the Saudi construction industry as seen from the above findings. These include the application of green roofs, recycling materials, use of recyclables, the use of passive lighting, green roofs and ventilation systems. However, due to the greatest importance and time constrains of this research, three areas of focus for further investigation are solar energy, rammed earth, and thermal insulation.

Chapter Six: Proposed Areas of Focus in the Research

6.1. Introduction

As aforementioned, three areas of focus (solar energy, rammed earth and thermal insulation) were chosen, for further study and analysis based on the background research and the results of the questionnaire and interviews. The areas of focus aim to enhance sustainability in the Saudi Arabian construction industry. Further, discussion relating the current status and the potential application of the focus areas can be found below.

However, as mentioned in some paragraphs in the thesis, there are other possible ways to achieve a sustainable construction. These include passive architecture (as in historic buildings in Saudi Arabia), balconies and overhang elements that create shadows and air through different rooms (crossed ventilation). In particular, passive design is a solution that has been proved in practice throughout the history. This is a great solution for the future and planned constructions. In this research's case study (chapter 7) the aim is to provide a solution to the current typical design (none-passive) that is being used in modern days without the change in design layout. It is believed that this could solve the current practices, in which, it is hard to change the design and current design practices. Additionally, water inside the building's courtyards provide internal humidity that help reduce the dry harsh weather. Green roofs, the colour of the external windows and shutters could play an important role in energy absorption. In fact, those mentioned sustainable elements are of great importance to enhance the building performance. However, the proposed ones are based on the current claims and needs of respondents as well as based on the literature reviews and historical practices. Without doubt the more sustainable elements applied the more performance we gain. In fact, this research is concentrated on the three proposed areas of focus with recommendation of using the other components mentioned in the research in a broader practices and preferably simultaneously.

6.2. Electricity and Solar Energy in Saudi Arabia

6.2.1. The Electricity Sector and Electricity Consumption in Saudi Arabia

It is important to understand the Saudi power sector status in numbers. This indicates the need for sustainability in the energy sector. Residential buildings are the main consumers of electricity in the country and the electricity sector one of the largest energy consuming sectors in Saudi Arabia. The structure of the power sector and the role of fuel in it determine the dynamics behind swings in oil demand. The power sector has been the main consumer of oil and gas in the last decade. The Saudi Electric Company (SEC) is the largest utility in the country that accounts for around 77 percent of installed capacity. In 2011, it consumed 363 million barrels of oil equivalent (boe) or around 995 thousand boe per day (Oxford Institute for Energy Studies, 2013). Since the data for the total power sector consumption are not publicly available, a 'back of the envelope' calculation implied a total consumption of liquid fuels and gas exceeding 1.2 million boe/d.

One of the key features seen over the last decade is the rapid increase in electricity demand in Saudi Arabia. This demand is driven by multiple factors such as harsh weather, population growth, improvements in standards of living, robust economic growth and a low energy pricing policy that encourages 'wasteful' consumption and creates wide distortions in the economy. In addition, electricity sold (a proxy for electricity demand) increased from 128,629 million kWh to 240,288 million kWh between 2003 and 2012, counting for about 78 percent increase in sold electricity (Fattouh, 2013). During the same period, the peak load increased from 23,938 MW to 51,939 MW with an increase of 217 percent according to same source.

The residential sector is the largest consumer of electricity in Saudi Arabia. According to Oxford Institute for Energy Studies (2013), it consumed more than half of the

electricity generated in the country in 2012 followed by industry (17 %), commercial (16 %) and governmental agencies (13 %). In addition, a survey conducted by the government discovered that about 70% of the total domestic electricity is consumed by air conditioning in the summer (Iqbal et al, 2003). Electricity is sold at highly subsidized prices, ranging from 1.3 to 6.9 US cents per kw/h depending on the type of end user, the consumption bracket and the time of use. Lately, the government has embarked on gradual reform of electricity prices. In 2010, electricity tariffs were increased for the industrial, government, and commercial sectors with an exception for the residential sector. Despite these increases, electricity prices in the Saudi Arabia remain very low.

Saudi Arabia is the main electricity producer and consumer in the Gulf States, with 272 billion kWh gross production in 2012 (Garwan, 2013). In fact, demand for electricity is experiencing a rapid growth in Saudi Arabia (about 8% annually) and peak demand is expected to be 70 GWe and 120 GWe by 2020 and 2032 respectively. In addition, population in the country is about 29 million and per capita consumption is about 8000 kWh/yr. According to Obaid and Mufti (2008), it is expected that, by 2025, the demand will double. The rapid growth in electricity demand is partially due to an inefficient use of electricity which is associated with highly subsidized tariffs (Alyousef and Stevens, 2011). Therefore, the country needs to take appropriate initiatives not only to boost its power generation capacity but also to make the residential sector more energy efficient in order to respond to the growing electricity demand.

A current study of the construction sector suggests that most of the projects being undertaken are residential buildings in order to meet the demand for new homes. The statistics provided by the Ministry of Municipal and Rural Affairs (2015), indicate that the majority of licenses issued for construction in the country are for residential buildings. Figure 6.1 shows these percentages in more detail. Furthermore, the

residential sector is set to experience a growth as the Saudi population is rising at a yearly rate of 2.5% and only 24% of the Saudi nationals have their own homes (Deloitte, 2010). According to Central Department of Statistics & Information (2013), around two-thirds of the population is under the age of 30 years and, in order to meet the needs of the constantly growing population, the country needs to build 2.32 million new homes by 2020 (Sidawi, 2009).

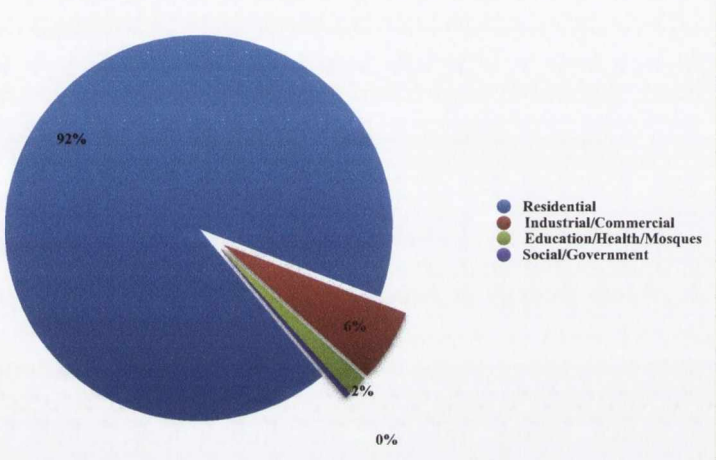


Figure 6 . 1: Building Permits Issued in 2013 in Saudi Arabia

(Alrashed, and Asif, 2014)

It is obvious that Saudi energy consumption pattern is unsustainable. The country consumes over one-quarter of its total oil production with 2.8 million barrels a day (Lahn and Stevens, 2011). This means that on a 'business as usual' trajectory, it would become a net oil importer in 2038 as shown in Figure 6.2. This, together with the associated environmental impact, evidences the urgency for the implementation of sustainable energy sources.

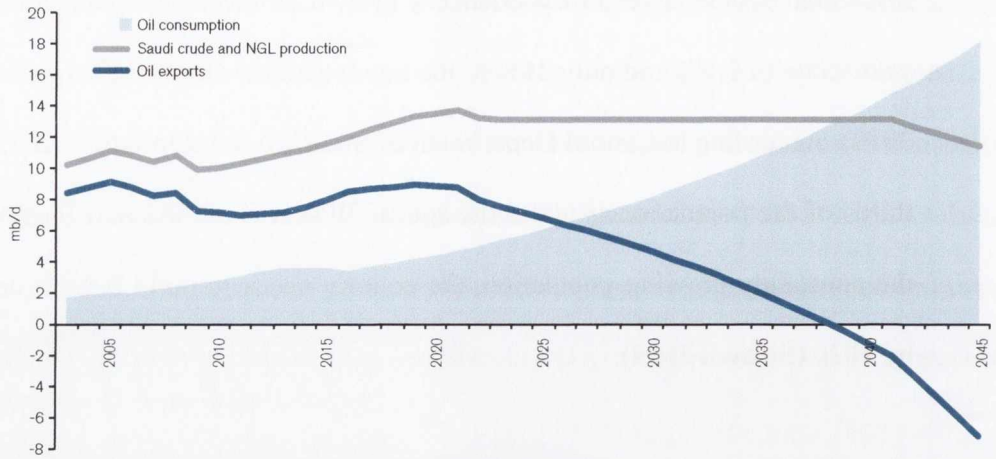


Figure 6 . 2: Saudi Arabia's oil balance on a business-as-usual trajectory (Lahn and Stevens, 2011)

6.2.2. Solar Energy in Saudi Arabia

Solar power in Saudi Arabia dates back to the 1970s and some solar projects are still in service today. Many are used in remote areas where grid connections are not economically efficient. Lately, Saudi Arabia has strongly encouraged the development of alternative energies supported by world-class local industries. King Abdullah bin Abdulaziz issued a Royal order A/35 that established King Abdullah City for Atomic and Renewable Energy (K.A. CARE) in 2010. This is a royal agency established to oversee renewable energy policy and introduce a number of sustainable energies into the country.

The government plans to produce a third of the nation's electricity from solar sources by 2032. Besides solar energy, this plan includes other renewable sources such as wind and geothermal as well as other non-renewable sources such as nuclear reactors. The reason behind this was to save more crude oil for export. However, this plan was delayed in 2015 as the government claims that it needs more time to assess the technologies to be used. 2040 is now the new target year according to Yamani (2015). In 2012, K.A. CARE claimed it would seek to build 41 gigawatts of solar power within two decades

and another 21 gigawatts of geothermal and wind power. However, today, only 1% of the country's energy supply comes from renewables, with a handful of solar projects producing a few megawatts each (Dipaola, 2015). Nevertheless, the K. A. CARE acknowledges solar energy as a solution to energy and environment-related problems (Figure 6.3).

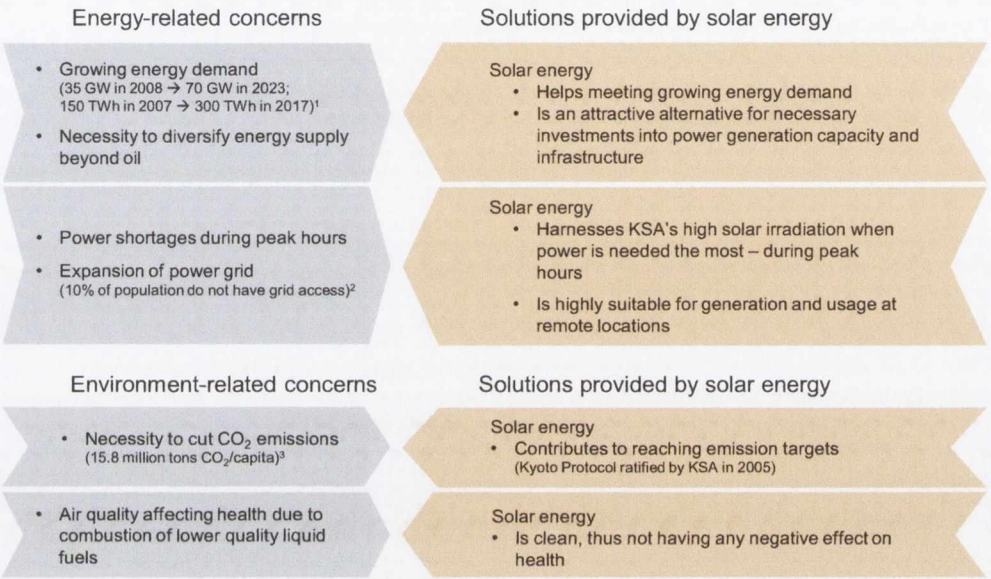


Figure 6 . 3: Solar energy as a solution to Saudi Arabia's energy-related and environment-related concerns.

(The KICP Annual Strategic Study, 2009)

Almasoud and Gandayh (2014), argued that Saudi Arabia with its geographical strategic location in the so-called Sun Belt and the widespread desert land with all year-round clear skies could become one of the largest solar photovoltaic (PVs) energy producers in future. According to Alawaji (2001), the average energy from sunlight falling on Saudi Arabia is 2200 thermal kWh/m^2 . Thus, it is worthwhile to attempt to generate clean energy in the country via direct sunlight through PV cells in both ground mounted and roof mounted systems. Figure 6.4 shows the map of solar irradiance in Saudi Arabia.

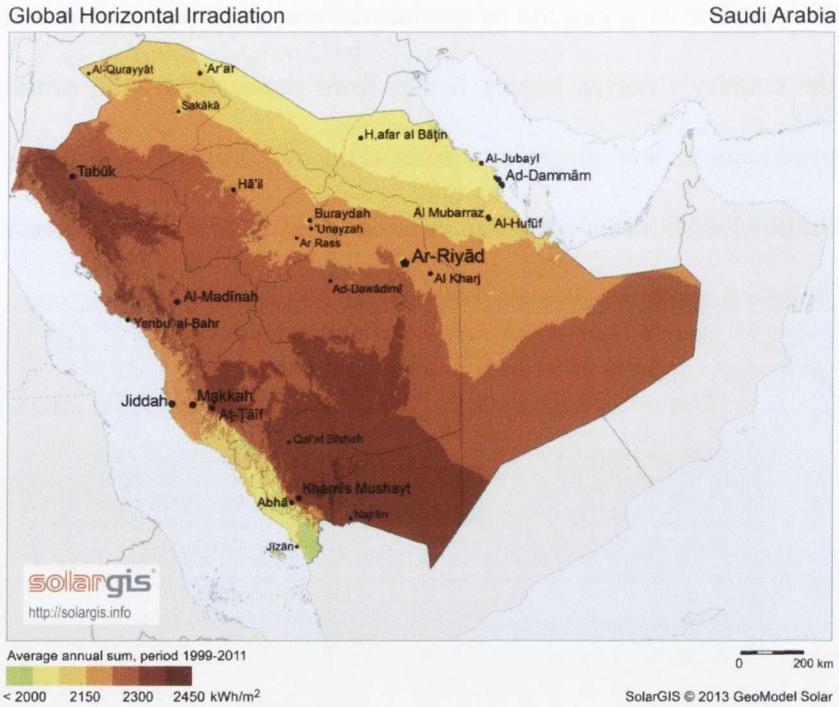


Figure 6 . 4: Solar irradiance in Saudi Arabia

(SolarGIS, 2013)

On view of the high potential for solar energy in the country, the fluctuations in decision-making and the delay in the national plan, this research will model the application of solar PV panels on residential buildings in an effort to provide a sustainable source for power that would reduce the load on the national reserves and the environment.

6.2.3. Solar Technologies in the world and technology chosen for this research

Two main solar technology systems exist: photovoltaic (PVs) and solar thermal technologies. PV technologies use the sun's light to generate electricity while solar thermal technologies use the sun's heat to generate electricity and provide hot water or steam for various applications and processes. Figure 6.5 shows these technologies.

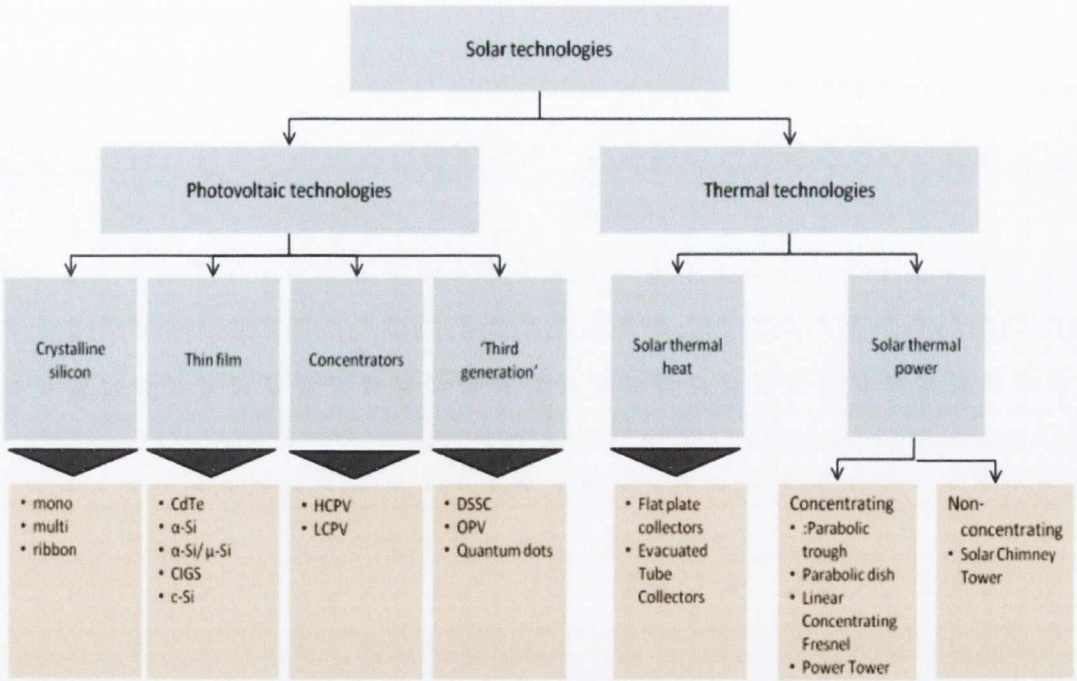


Figure 6 . 5: Solar energy technologies

(The KICP Annual Strategic Study, 2009)

Almost 90% of the world's photovoltaics today are based on some variation of silicon (Maehlum, 2015). In 2011, about 95% of all shipments by U.S. manufacturers for the residential sector were crystalline silicon solar panels (U.S. Energy Information Administration, 2013). Silicon with a range of purity is used in PVs and there are a number of suitable PV panels for application in buildings. These include crystalline silicon (c-Si), monocrystalline silicon solar cells, polycrystalline silicon solar cells, string ribbon solar cells, thin-film solar cells (TFSC), amorphous silicon (a-Si) solar cells, cadmium telluride (CdTe) solar cells, copper indium gallium selenide (CIS/CIGS) solar cells, and building-integrated photovoltaics (BIPV) systems. Monocrystalline silicon solar cells (MSSC) installed on the roof of residential buildings is the option chosen in this research. The advantages and reasons behind choosing this specific type of solar panels are discussed below. As aforementioned PV application is proposed for residential buildings as they are the main electricity consumers (Figure 6.6) and the

majority of construction permits in Saudi Arabia are issued for residential buildings with a great potential to enhance sustainability in the short term.

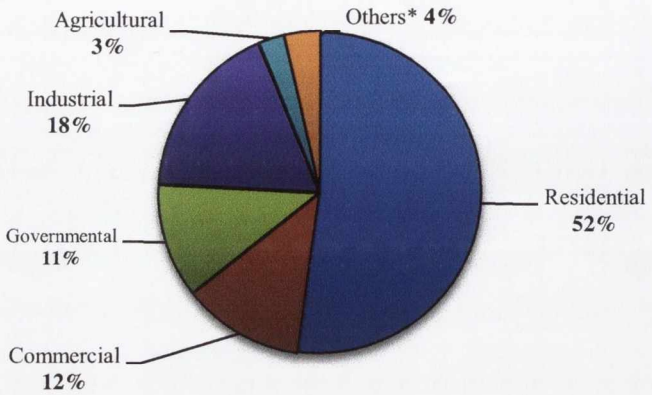


Figure 6 . 6: Electricity consumption by sector in Saudi Arabia

(Alrashed and Asif, 2014)

MSSC cells are made of monocrystalline silicon (mono-Si) also known as single-crystalline silicon (single-crystal-Si). They are easily recognizable by their external even coloring and uniform look, indicating high-purity silicon. In a cylindrical shape, monocrystalline solar cells are made out of silicon ingots. For performance optimization and cost reductions, the four sides of each single cell are cut out of the cylindrical ingots to make a silicon wafer that gives monocrystalline solar panels their characteristic look. Advantages of this specific type of PV system include their highest efficiency rates since they are made out of the highest-grade silicon with efficiency rates typically ranging from 15 to 20% (Maehlum, 2015). In addition, these solar panels yield the highest power outputs requiring the least amount of space compared to any other types of solar panels. Therefore, they are space-efficient and have valuable characteristics for application in residential building's roofs. According to the above source, this type of solar panels produce up to four times the amount of electricity than thin-film solar panels. A further reason behind selecting this specific type of solar PV for application in Saudi residential buildings is the fact that monocrystalline solar panels are more efficient in warm

weather conditions. This is due to the fact that its performance suffers as temperature goes up, but less so than polycrystalline and other solar solar panels (Maehlum, 2015). Finally, monocrystalline solar panels have a longer life than any other types of solar panels in the market. The KAUST Industry Collaboration Program (KICP) has also recommended these panels for application in Saudi Arabia based on their long-term potential (KICP, 2009). In this report, the most attractive solar technologies and research fields for Saudi Arabia have been identified in a two-step approach covering both market potential and synergies for Saudi Arabia. In the selection process, five solar technologies prevailed and crystalline silicon PV was identified as the best PV technology with high cell efficiency still bearing significant potential for cost reduction. Figure 6.7 shows solar technologies recommended for application in Saudi Arabia.

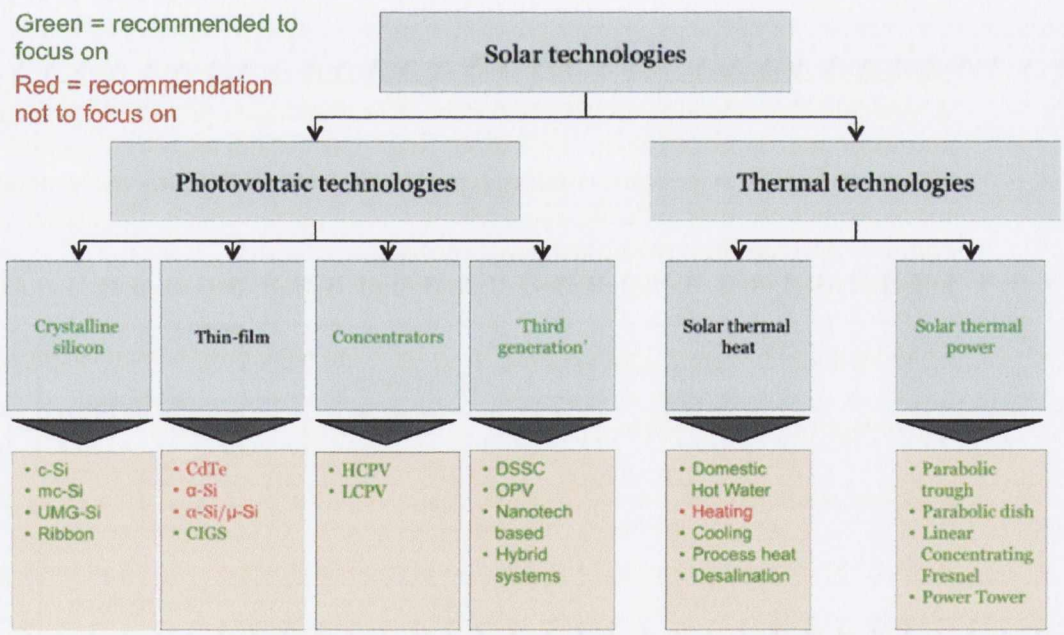


Figure 6 . 7: Recommended solar application focus in future of Saudi Arabia

(The KICP Annual Strategic Study, 2009)

The silicon for crystalline PVs is manufactured in a two-step process by refining appropriate quartz sand first to low-purity metallurgic grade silicon and then to high-purity solar-grade (polysilicon). Silicon and silicon-based products have the potential to

be produced in Saudi Arabia ,which is a further reason behind choosing this type of PVs systems in this investigation. According to same source, Saudi Arabia's relative global position is best for silicon manufacturing. One of the potential sites for silicon manufacturing is King Abdulla Economic City (KAEC) in the Makkah Province where the capital city Mecca is due to local availability of silicon in the region.

6.2.4. Life Cycle of PVs

Life cycle of PVs requires the consideration of environmental impacts from the inception of the solar panel during the extraction phase until the final disposal phase of the material. Life cycle assessments for monocrystalline PVs vary largely based on both location of production due to the grid electricity, which is used in the factory, and location of the study because of variation of solar radiation across different climates (Kittner et al. 2012).

A typical life cycle assessment breaks the PVs generation process into several steps as shown in Figure 6.8. Some studies reported that up to 80% of the embodied energy could be derived from manufacturing processes.

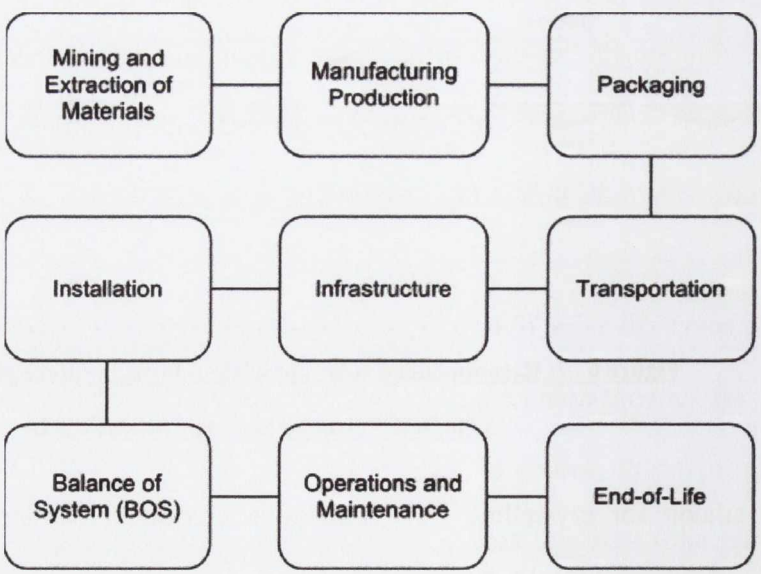


Figure 6 . 8: General Steps Considered in Life Cycle Assesment Studies of PV Systems (Kittner et al. 2012)

In fact, material production and component manufacturing account for more than 80% of the life cycle greenhouse gas emissions because during the use phase, emissions are negligible and data related to the disposal stage are rather scarce and variable (Hsu et al. 2012). This encourages the emphasis of future improvements on the production phase to reduce life cycle greenhouse gas emissions.

The most direct way to reduce greenhouse gases impacts from the production of monocrystalline solar panels is to reduce the embodied energy. However, there are different strategies to reduce the energy required to construct this specific type of PVs. Figure 6.9 summarizes the approximate embodied energy for different steps in the production of grid-connected monocrystalline PV.

The Czochralski (CZ Step) Process comprises the bulk of the energy required for production of monocrystalline modules (34% of the embodied energy). Additionally, silicon purification and cell process energy contribute to a large portion (a combined 44% of the embodied energy). The Inverter and Balance of System (BOS) may contribute to approximately 6% of the embodied energy. In fact, this value varies depending on the location of deployment and necessary infrastructure to complete the grid connection process. Steps are highlighted with potential for life cycle greenhouse gas emission reduction in Figure 6.9 (Kittner et al. 2012).

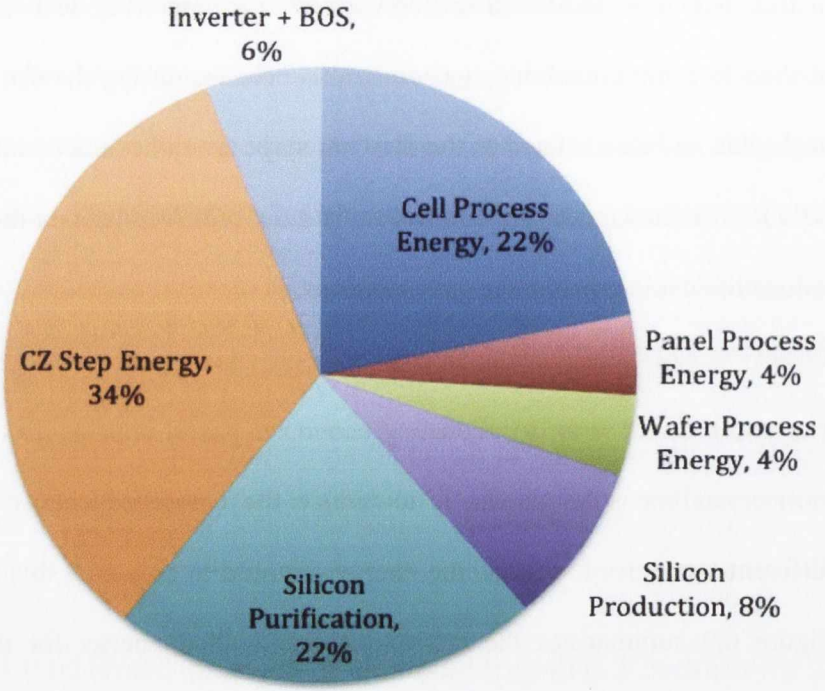


Figure 6 . 9: The Distribution of Embodied Energy Requirements for Monocrystalline PV (Kittner et al. 2012)

In general, the life-cycle stages of PVs involve the production of raw materials, their processing and purification, the manufacture of modules and balance of system (BOS) components, the installation and use of the systems and their decommissioning and disposal or recycling as shown in Figure 6.10 (Hsu et al. 2012).

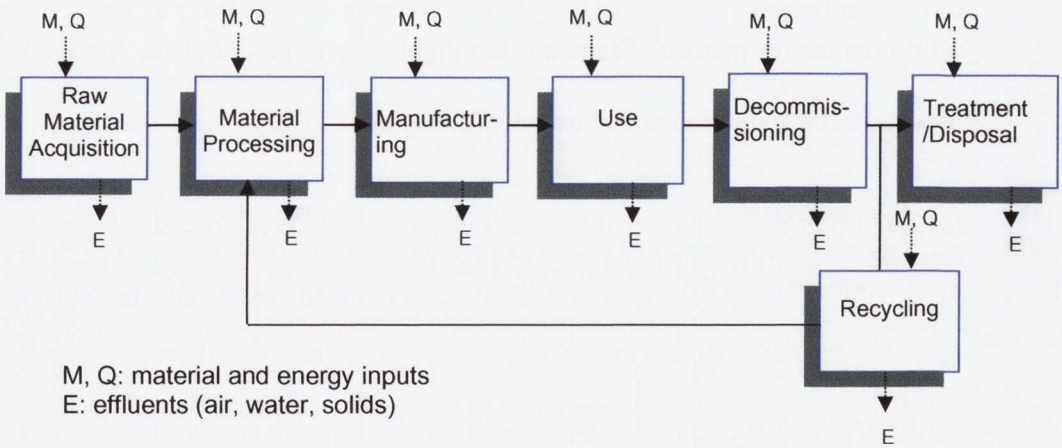


Figure 6 . 10: Flow of the Life-Cycle Stages for PV Systems (Hsu et al. 2012)

With the aforementioned reasons on why using the solar PVs as a sustainable solution, it is a fact that this choice was based on the recommendation of the questionnaire and interviews respondents as the majority urged the exploit of solar energy. This was due to the abundance of strong sunlight almost all around the year, the high rate of energy consumption from fossil fuel (unsustainable practice) and above that the utilization of natural resources in a sustainable manner. In addition, the selection of this solution is also to demonstrate (on local scale) the benefits and the importance of solar PVs on the construction industry and the country as a whole to the decision makers, businesses, manufacturers, professionals and other stakeholders.

6.3. Rammed Earth as a Sustainable Building Material

6.3.1. Rammed Earth

As one sustainable element selected as a solution for further investigation based on literature review, historic buildings and current sustainable practices, rammed earth is further explained here with regard to Saudi Arabia. This section provides further details on rammed earth locations, applications and advantages.

The reasons behind selecting rammed earth as a sustainable solution are many. It is due to the fact that this method used to be one of main construction methods in the country's history. In fact, the research aimed at the reintroduction of this practice since many of questionnaire and interviews' respondents also suggested for the reuse of historical sustainable methods like earthen materials and techniques. In addition, the availability of this material across the country is an advantage to drive the pursued change. Other reasons are discussed below as many advantages could be gained using rammed earth methods in residential buildings.

In fact, earthen materials have been used in different parts of the world for thousands of years. Figure 6.11 shows earth construction areas in the world. A major part of Saudi Arabia used earthen materials for building. However, rammed earth as well as other earthen materials is not common in current construction activities in the country. According to Prince Sultan Bin Salman (2011), *"What matters is that mud construction, as a know-how and technology disappeared from Saudi cities and villages since 1960s after the introduction of the new building materials and technology in the Kingdom."* As an attempt to bring back earthen materials to the construction industry, Prince Sultan Bin Salman had introduced a project to rebuild a farmhouse in Al- Udhaibat, located in Wadi Hanifia in the old city of Dir'iyyah near Riyadh (Facey, 1999). They were trying to revive mud construction technology by starting a project that can be considered in the future as the laboratory for this old methodology. The project was rebuilt completely, for safety reasons, by using the same old techniques of mud construction used in historic buildings of Saudi Arabia. This is a unique example of the use of past materials and technologies for modern applications in the last few decades. Figure 6.12 shows Al-Udhaibat's farmhouse after completion in late 1980's.

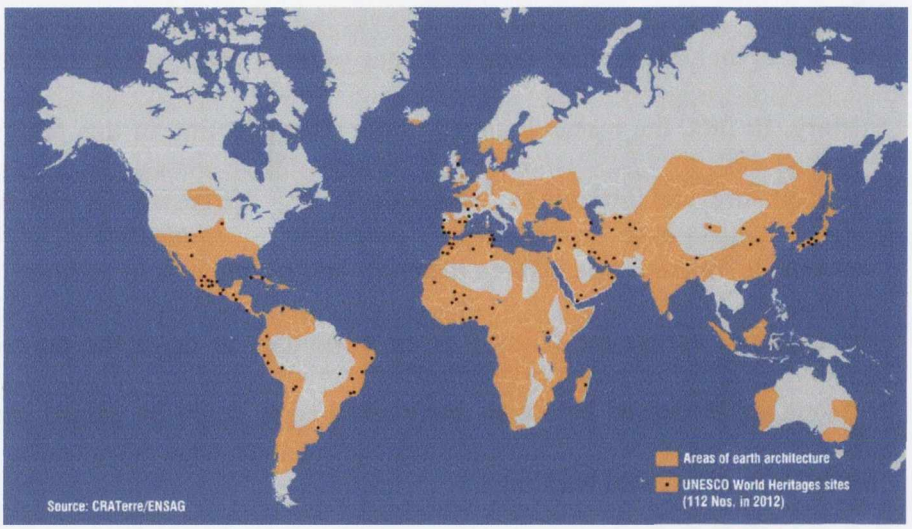


Figure 6 . 11: Earth construction areas of the world

(http://www.earth-auroville.com)

Figure 6 . 12: Al- Udhaibat's farmhouse

(http://www.al-turath.com)

As mentioned earlier, rammed earth construction carries social, economic and environmental benefits (Hueneke and Wright, 2004). These benefits are even more positive in developing countries where material costs outweigh labour costs, and other construction materials and technologies may not be available (Ngowi, 1997). The environmental and financial impact of a building is significantly reduced when the raw material is obtained on-site (Walker et al. 2001). Employment of local unskilled labour force and the elimination of the cost of accommodation and transport of labour brought from distance are some advantages of using this construction method due to its easiness and simplicity in application. Rammed earth construction has a significantly lower embodied energy and carbon footprint than conventional materials such as concrete and steel.

There are many advantages of applying rammed earth in modern construction. These include the following:

1. Low embodied energy and low carbon emissions
2. Recyclable
3. Locally available
4. Rammed earth offers wide variety of textures and finishes
5. Strength can be made using stabilized rammed earth walls
6. High thermal mass
7. Lower cost

Rammed earth wall buildings are assumed to perform in a thermally desirable way because their large thermal mass can effectively delay the heat transmission through the external walls. This can be particularly seen in summer when peak indoor temperatures are delayed by a long thermal time lag (Donga et al. 2014). In addition, Allinson and Hall (2010), indicated that rammed earth walls could potentially save the energy for indoor humidification.

According to Minke (2000), advantages of rammed earth incorporate high aesthetic appeal, very low embodied energy, and passive hygroscopic humidity regulation of indoor areas. In addition, rammed earth buildings create thermal mass structures that cool the interior spaces during hot, dry summers and absorb heat during cold winters (Schexnayder et al. 2013). Thus, this technique is suitable for the Saudi Arabian climate.

In addition, the history of earth construction in Saudi Arabia (discussed in chapter 1) goes back to hundreds of years. Local builders used different earth materials to build dwellings. However, after the oil boom in 1970s, the construction industry in Saudi Arabia became dependent on conventional materials with no regard for the environment and natural resources. The 'earth' used for making rammed earth generally refers to a sandy loam sub-soil (Matthew and Djerbib, 2003) which is abundant in Saudi Arabia.

The project will focus on the application of this material to Saudi residential building, as it is the major type of ongoing construction and main energy consumer in the country.

6.3.2. Proposed Context of Rammed Earth Application

The research proposes the use of stabilized rammed earth as an alternative to the current Portland cement based materials in residential buildings. The main stabilizers for rammed earth are Portland cement and lime. However, lime-stabilized rammed earth will be the focus of this project as the incorporation of Portland cement reduces sustainability and increases both cost and environmental impact (Ciancio and Boulter, 2012) (Walker et al. 2001). Also, lime stabilization improves strength, stiffness, plasticity/workability and water adsorption of the raw soil (Carraro et al. 2013). In addition, there is a conflicting result for the sustainability degree of lime versus the Portland cement in terms of their thermal and embodied energy in the literature (Walker et al. 2001) (Venkatarama et al. 2001). The results are, in fact, depending on the mineralogy of the clay, availability and transportation. Moreover, lime stabilization can represent a more efficient solution than Portland cement for the material mechanical properties enhancements. *"It is well established that using Portland cement to stabilize clayey soils does not always produce the expected enhancements in terms of material performance"* (Carraro et al. 2013).

6.4. Thermal Insulation

6.4.1. Building insulation and energy saving

Energy resources, namely natural gas, oil and nuclear fusion are expensive and will become increasingly expensive or depleted in future. In a global scale, the awareness of energy and environment issues has increased research on energy saving methods. One of the main energy conservation techniques used globally is the use of thermal insulation in residential buildings. In Saudi Arabia and the Gulf countries, studies have showed that these countries could save up to 33% of the annual energy consumption by using

insulation in buildings (Al-Rabghi and Al-Johani, 1997) (Danny and Parker, 1977). Thermal insulation (natural or synthetic) can be applied to the building envelope to reduce the thermal transmittance of walls, roofs, floors, windows and doors and limit the transfer of heat from the exterior during the summer and the heat transfer from the interior during the winter.

6.4.2. Building insulation status in Saudi Arabia

Thermal insulation in buildings will soon be mandatory in 23 cities and towns across Saudi Arabia according to Global Insulation, 2014. In support of this, the Minister of Municipal and Rural Affairs said that the measures would be a pre-requisite when applying for electricity connections. To implement the policy, municipalities and engineering consultants will coordinate with Saudi Electricity Company (SEC). According to Laurie Balbo (2014), only 25.4% of the Saudi Arabia's buildings were thermally insulated in 2014. In the residential sector, the percentage of insulated buildings is about 30% as shown in Figure 6.13.

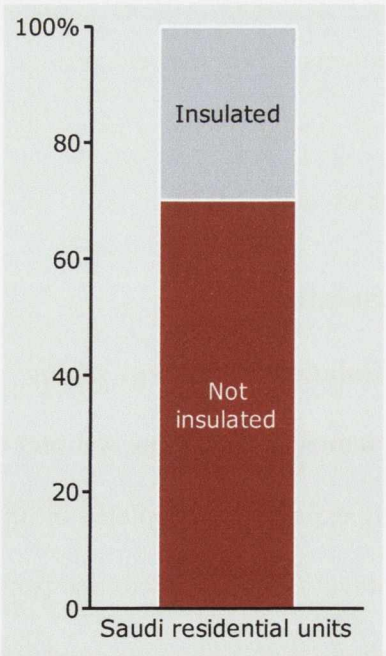


Figure 6 . 13: Insulation in Saudi residential buildings

(Naif Alabbadi , 2013)

However, According to Al Rashodi (2014), *"the Saudi code is based on international standards which specify insulation values with respect to roofs, walls and floors, based on the requirements of US and EU climate zones. That makes for a solid point of reference, but KSA codes need to reflect the climactic and insulation conditions of this specific region"*.

6.4.3. Current insulation materials used in Saudi Buildings

In newly constructed houses, wall structures vary from one region to another. However, the building materials employed are stone, concrete, bricks and the required steel bars for reinforcement. Table 6.1 lists some typical wall (solid walls except Wall IV) structures for buildings and their thermal characteristics, including the conductance U-value, and thermal resistance.

Wall Type	Thickness of Wall (m)	Thermal Conductivity (W/mK)	Thermal Conductance U (W/m^2K)	Wall Resistance (m^2 K/W)
Wall I				
External plaster	0.02	1.20		
Hollow bricks	0.20	0.90	2.25	0.44
Internal plaster	0.03	1.20		
Wall II				
External plaster	0.02	1.20		
Concrete	0.20	1.75	2.98	0.336
Internal plaster	0.03	1.20		
Wall III				
Stone	0.20	1.70		
Concrete	0.07	1.75	2.28	0.438
Hollow bricks	0.20	0.90		
Plaster	0.03	1.20		
Wall IV				
Stone	0.20	1.70		
Concrete	0.20	1.75	1.62	0.617
Air gap	0.05	0.28		
Bricks	0.10	0.90		
Plaster	0.03	1.20		

Table 6 . 1: Structures and thermal characteristics of walls used mostly in Saudi Arabian residential buildings

(Ahmad, 2002)

In Table 6.1, the wall I refers to a perforated fired-clay brick wall while wall II is a solid concrete wall. Additionally, wall III is a solid concrete wall with stone cladding and wall IV is a cavity wall with concrete and concrete blocks with a stone cladding as a finishing. Wall I is the most common structure in residential buildings in Saudi Arabia, which consists of a hollow brick layer (perforated fired-clay brick) and a plaster layer applied to both the inside and outside. In order to improve the thermal resistance, a small number of new buildings employ cavity wall with concrete block similar to wall IV in table 6.1.

However, thermal insulation is usually applied on external walls and is unlikely to be applied within roofs in Saudi Arabian residences (Ahmad, 2004) (Al-saadi and Budaiwi, 2007). The most common thermal insulation materials used are Polystyrene and Polyurethane with a typical thickness of 5 centimeters (Ahmad, 2002). In fact, these are widespread as different manufacturers produce them in the country. Other types of main thermal insulation materials used in Saudi Arabia include natural wool, mineral wool and foam.

6.4.4. Proposed materials for insulation in Saudi residential buildings

In February 2015, a new sustainable insulation material was introduced to the Saudi market. This material is called Knauf Insulation mineral wool with ECOSE® Technology and is produced by Knauf Insulation, a multinational company present in more than 37 countries. As indicated by Knauf Insulation Company, the insulation is available in the construction materials market and suitable for Saudi Arabian climate conditions. In addition, it is manufactured from naturally occurring and/or recycled raw materials, and bonded using a bio-based technology that is free from formaldehyde, phenols, and acrylics. It also contains no artificial colours, bleach or dyes. According to the producer, it contributes to improve indoor air quality compared to other conventional

mineral wool and has a lower embodied energy that reduces impact on environment. It also reduces contaminant manufacturing emissions and workplace exposures and it is a cost competitive compared to traditional mineral wool. The reason behind using this type of insulation among other types available in the local market is the fact that this is certified as a sustainable thermal insulation. In contrast, the other types in the market are made of petrochemicals and have impacts on human health and the environment.

The properties of this material comply with the European Norm (Table 6.2). Figures 6.14 to 6.19 show more details of this thermal insulation as provided by the supplier. As it can be seen from these figures, its thermal conductivity is comparable to that of traditional mineral wool (Figure 6.14) while its durability is superior with a lower water absorption (Figure 6.15). Also, this material has a greater thickness recovery and lower thickness loss over time (Figures 6.17 to 6.18). Due to these properties, this insulation material was chosen to be modeled in Chapter 7.

Product performance of mineral wool with ECOSE Technology	In accordance with EN 13162:2008 and
For all applications	
Thermal resistance and thermal conductivity	EN 12667, EN 12939
Length and width	EN 822
Thickness	EN 823
Squareness	EN 824
Flatness	EN 825
Dimensional stability	EN 1604
Tensile strength parallel to faces	EN 1608
Reaction to fire	EN 13501-1
Durability characteristics	
For specific applications	
Dimensional stability under specified conditions	EN 1604
Compressive stress or compressive strength	EN 826
Tensile strength perpendicular to faces	EN 1607
Point load	EN 12430
Compressive creep	EN 1606
Water absorption	EN 1609, EN 12087
Water vapour transmission	EN 12086
Dynamic stiffness	EN 29052-1
Compressibility	EN 12431, EN 1606
Sound absorption	EN ISO 354, EN ISO 11654
Air flow resistivity	EN 29053

Table 6 . 2: Product performance of mineral wool with ECOSE Technology

(Knauf Insulation , 2015)

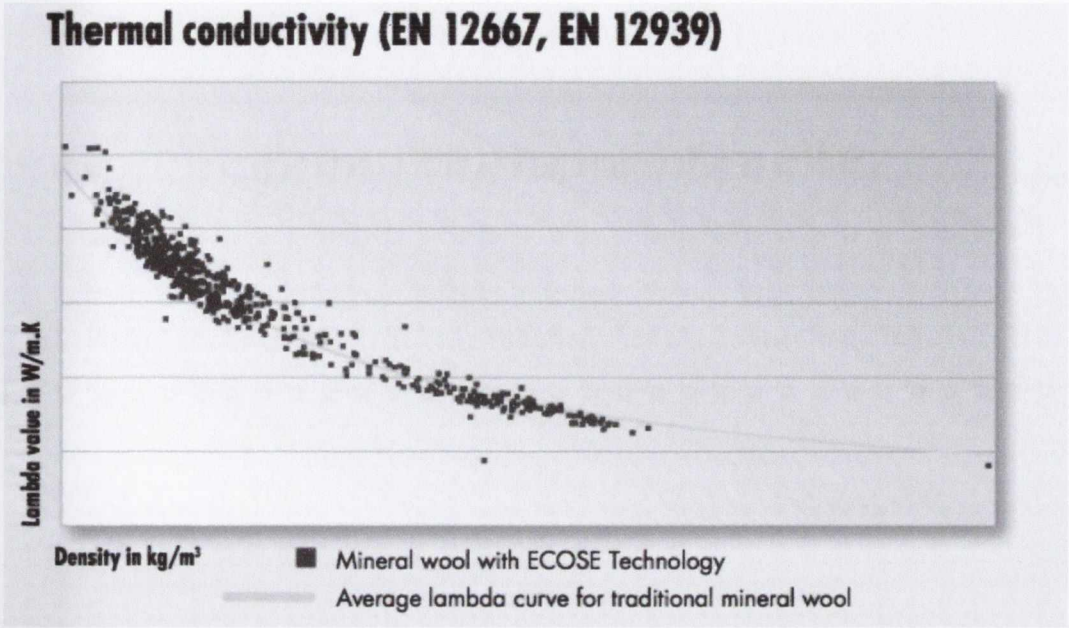


Figure 6 . 14: Thermal conductivity properties are equivalent to traditional mineral wool

(Knauf Insulation , 2015)

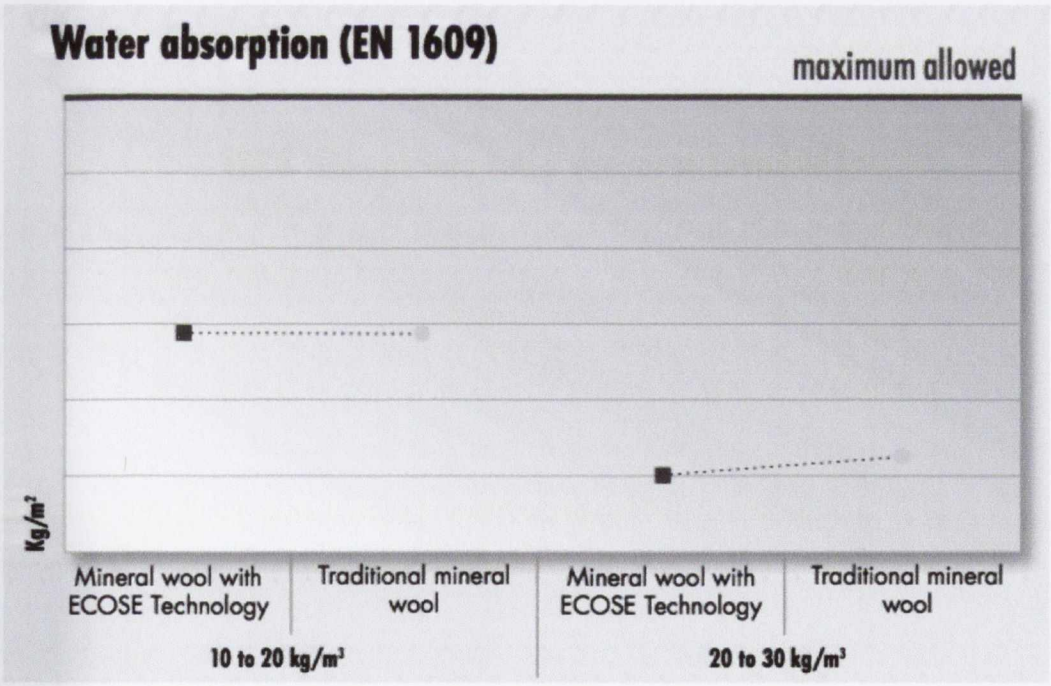


Figure 6 . 15: performance is equally or better than traditional mineral wool for applications where water repellency is required

(Knauf Insulation , 2015)

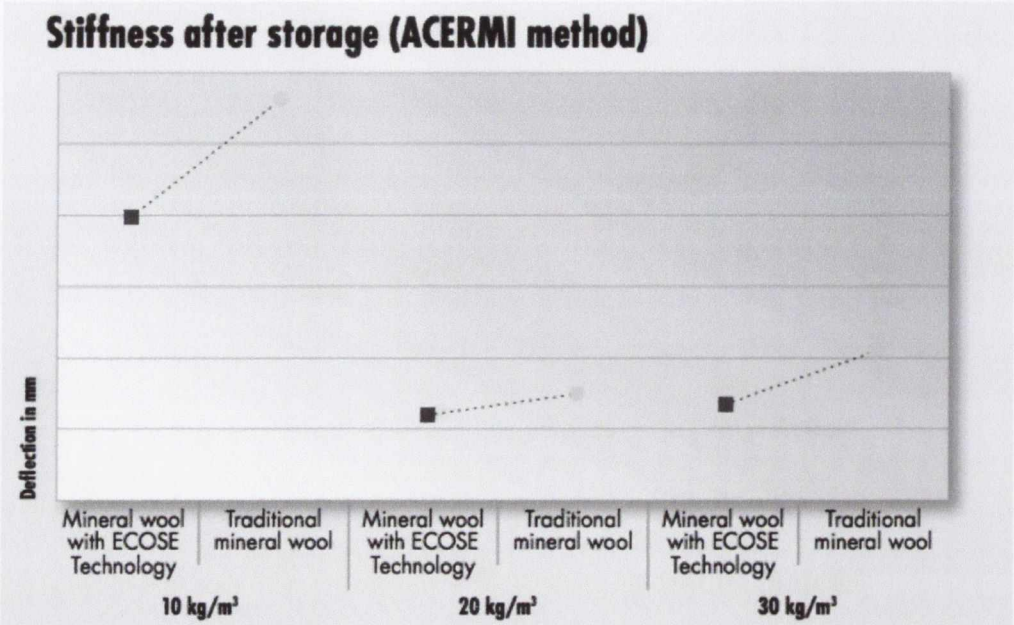


Figure 6 . 16: Stiffness is equal or better compared to traditional mineral wool slabs

(Knauf Insulation , 2015)

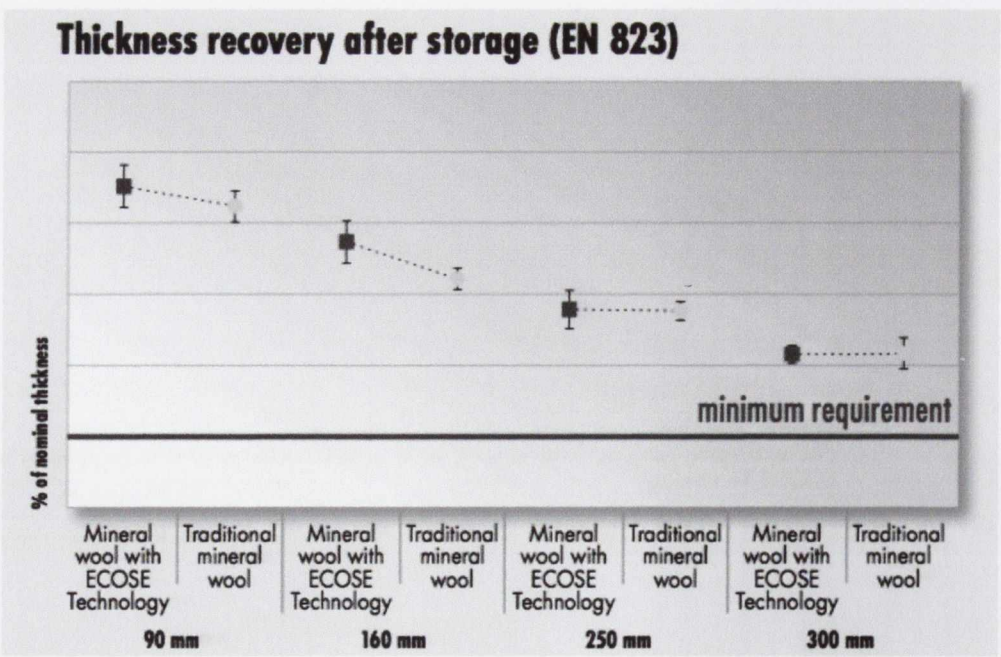


Figure 6 . 17: The product recovery is equal or better compared to traditional glass mineral wool

(Knauf Insulation , 2015)

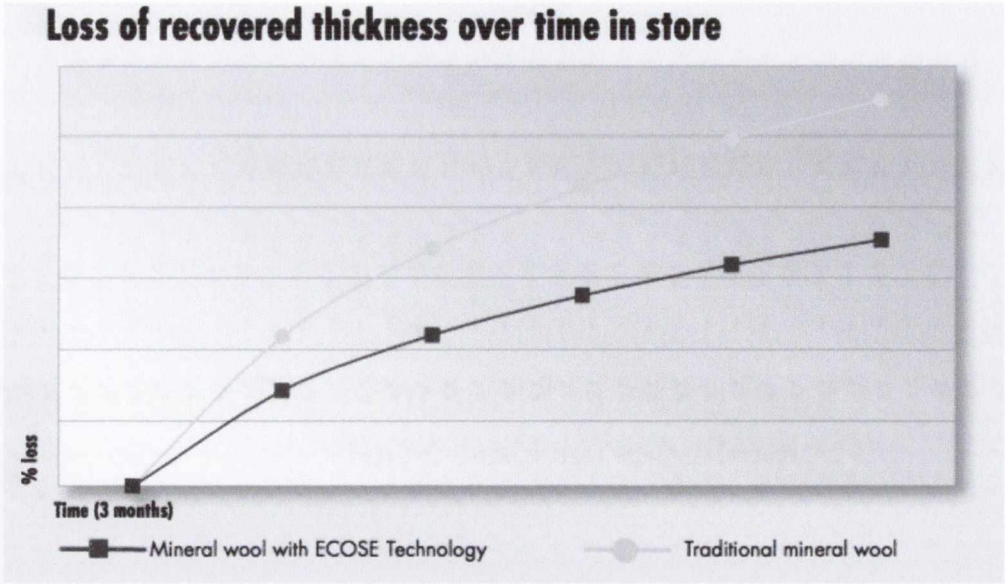


Figure 6 . 18: The decay of thickness recovery is slower compared to traditional mineral wool

(Knauf Insulation , 2015)

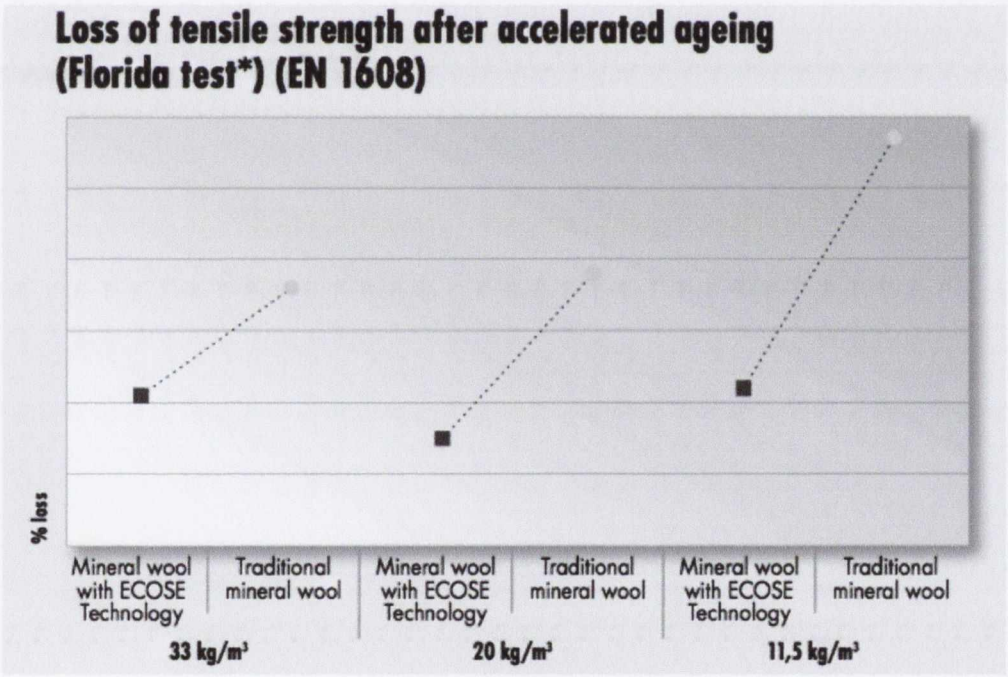


Figure 6 . 19: The loss of tensile strength over time is significantly less compared to traditional mineral wool

(Knauf Insulation , 2015)

Chapter Seven: Simulation and Analysis of Green Technologies on Case Study

7.1. Introduction

This chapter describes the case study selected in which the proposed sustainable elements are applied. The alterations to the base case based on the proposed three areas of research focus have shown tremendous improvements. These can be seen in the huge reduction in the amount of energy required for the building. The sections below describe this in more detail.

7.2. Case Study Description

The selected case study is a typical residential building situated in the city of Mecca (Figures 7.1 and 7.2). The recently built residential building is located in a new district that has witnessed many construction activities in the recent past.

The building is a two-story dwelling with a total of six apartments. Each apartment accommodates 6 residents with an assigned car parking space in front of the building. According to the Saudi Ministry of Economy and Planning, this building represents the most common type of residence in the country. In addition, the materials and construction elements used in the building are the most commonly adopted in Saudi Arabia nowadays. Table 7.1 shows some key features of the case study while table 7.2 shows the construction materials used in this building with their thermal properties. The case study building includes a total land area of 875 square meters. Figures 7.3 and 7.4 show the floor plans and elevations.

Figure 7 . 1: Location of Mecca

(World Factbook, 2015)

Figure 7 . 2: Aerial view of the case study and its urban context

(www.maps.google.com)

Figure 7 . 3: Floor plans of the case study

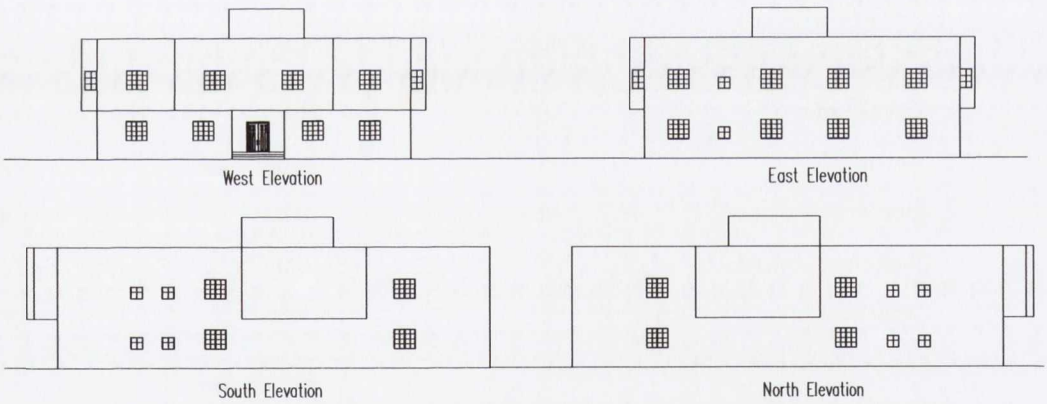


Figure 7 . 4: Elevations of the case study

Feature	Description
Ground floor area	605 m^2
First floor area	650 m^2
Total glazed area	58 m^2
Total external walls area	792 m^2
Total roof area	650 m^2

Table 7 . 1: Key Features of the case study building

Material	Thickness mm	Density kg/m^3	Conductivity W/m K
(A) Ground floor, including earth layer			
Ceramic tiles	25	2300	1.3
Mortar	25	2800	0.88
Sandstone	100	2200	1.83
Reinforced concrete	100	2300	2.3
Asphalt insulation	5	2100	0.7
Concrete high density	50	2400	2.0
Base-course stone	150	2000	1.40
Earth	20	1460	1.28
(B) External walls from outside to inside			
Plaster (dense)	20	1300	0.5
Concrete blocks	200	600	0.19
Plaster (light)	25	600	0.16
(C) Internal partitions			
Plaster (light)	25	600	0.16
Concrete blocks	100	600	0.19
Plaster (light)	25	600	0.16
(D) Intermediate floors			
Ceramic tiles	30	2300	1.3
Mortar	25	2800	0.88
Sand stone	50	2200	1.83
Reinforced concrete	120	2300	2.3
Concrete blocks	250	900	0.25
Plaster (dense)	20	1300	0.5
(E) Roof			
Ceramic tiles	20	2300	1.3
Mortar	10	2800	0.88
Sand stone	50	2200	1.83
Asphalt insulation	5	2100	0.7
Reinforced concrete	150	2300	2.3
Concrete blocks	200	900	0.25
Plaster (dense)	20	1300	0.5

Table 7 . 2: Specification of the building materials and their thermal properties

(Semmat Consultants, 2015)

7.3. Simulation Software

There are many different types of simulation software in the market that help understanding buildings performance in terms of energy use and consumption. Among them is the Integrated Environmental Solutions Virtual Environment (IES-VE) (Version 2015.0.0.), which will be used in this research to measure the building energy performance of the case study. The software uses a dynamic thermal analysis of the building model via many different tools including ModelIT, ApacheSIM, MacroFlo and SunCast. These are the tools that the software uses as a way toward the analysis of the case study building.

The simulation of the base case is firstly inputted in the software. Next, the new proposed sustainable elements are entered. Results and findings are discussed below.

7.4. Dynamic Thermal Model

A dynamic thermal model was built within IES-VE thermal modeling software based on 3D model of the case study by entering the relevant technical data in the case study. This constitutes the basic in which the model will work. The building modeled is shown below in figures 7.5 and 7.6.

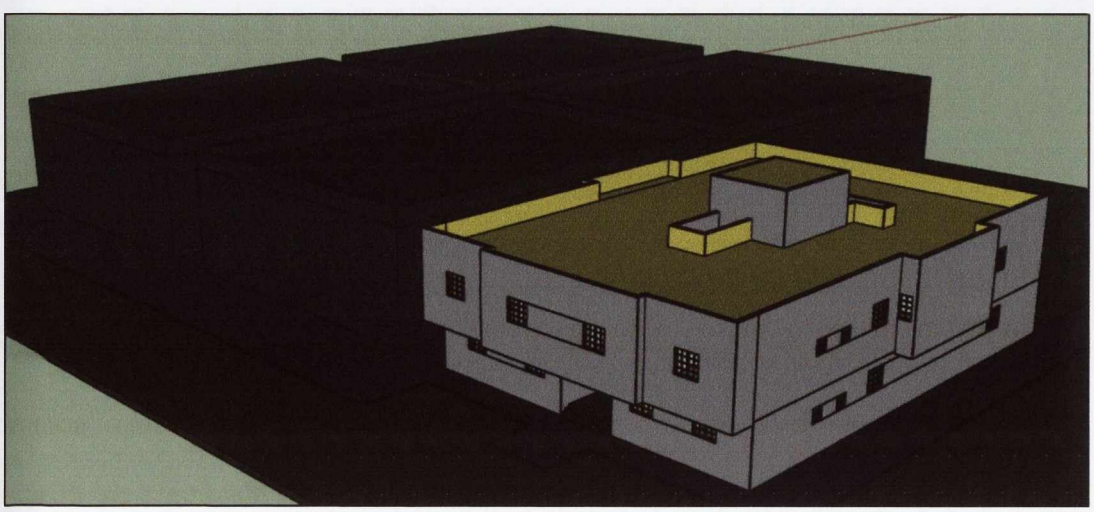


Figure 7 . 5: 3D model of the case study building

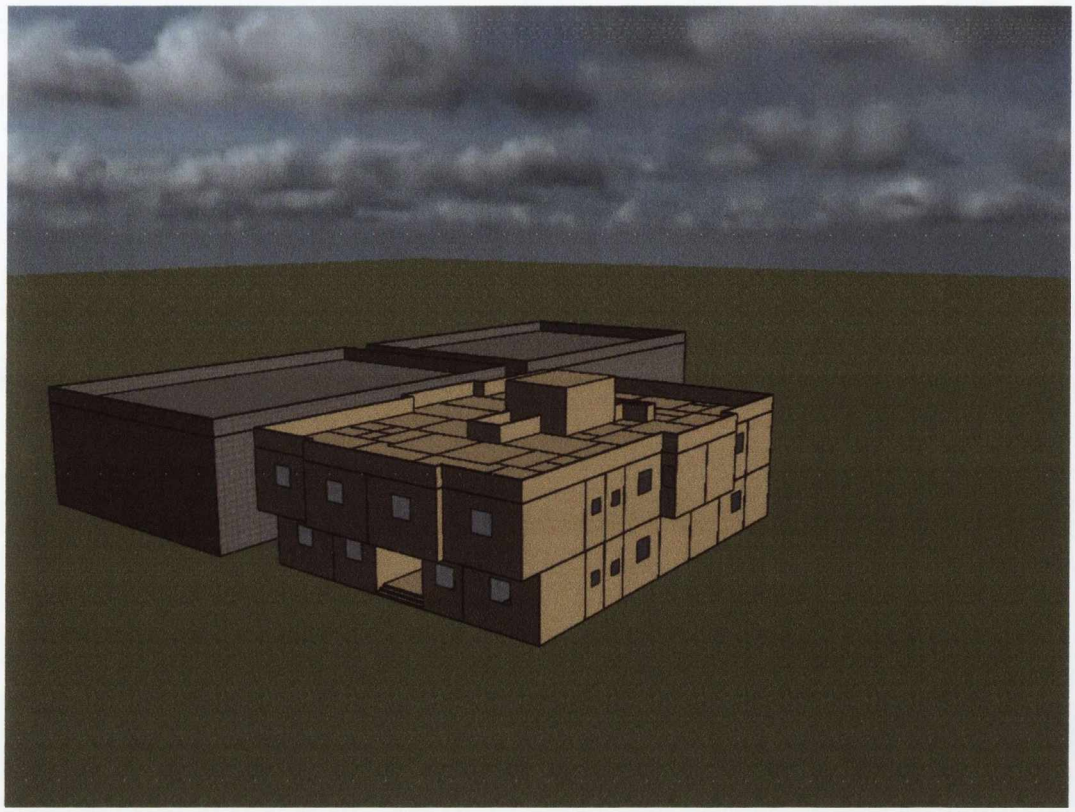


Figure 7 . 6: Model Developed in IES-VE Dynamic Thermal Modeling Software

7.5. Model Validation

In fact, the IES-VE software can simulate numerous results for the energy flow and environmental conditions within a building. According to Beevor (2010), the accuracy of the real world testing and of the ability of the IES-VE simulations to provide accurate building performance data has been already validated through many of tests conducted several times. In the case of the total energy values, the analysis the IES-VE concluded that there was no considerable statistical difference in the mean values between simulation result and measuring data (Nikpour et al, 2013).

For the case study building in this research, it has been validated that the IES-VE model is capable of making estimates and predictions to a reasonable level of accuracy. In fact, the simulation results of the existing condition of the building were compared to the actual results provided by the source of the case study. The results showed no major

differences between data obtained from the software and data provided by the original source. In fact, both results were similar as it is unreasonable to expect any model to provide perfect predictions, but through the comparison of model predictions against real measurements provided by the building owner, a reasonable level of confidence in the IES-VE model estimates has been achieved. This validation of the model made it clear to move to the next step in the simulation process as detailed in the next sections.

7.6. Weather File

In order to determine accurate building energy analysis, a specific site location of Mecca (Makkah) Saudi Arabia was assigned to the building thermal model. Using a local weather file, accurate site environmental conditions such as external temperature and solar effect on the building can be modeled in an annual simulation. The sun path diagram for Mecca is also provided below in Figure 7.7, which reflects the position of the sun in the sky at various times throughout the year. According to the annual weather file used in the modeling, the outside air temperature is provided below in Figure 7.8.

Sun path diagrams are used to read the solar azimuth and altitude throughout the day and year for a given position on the earth. They can be compared to a photograph of the sky, taken looking straight up towards the zenith, with a 180° fish-eye lens. The paths of the sun at different times of the year can then be projected onto this flattened hemisphere for any location on Earth, in this case Mecca is used.

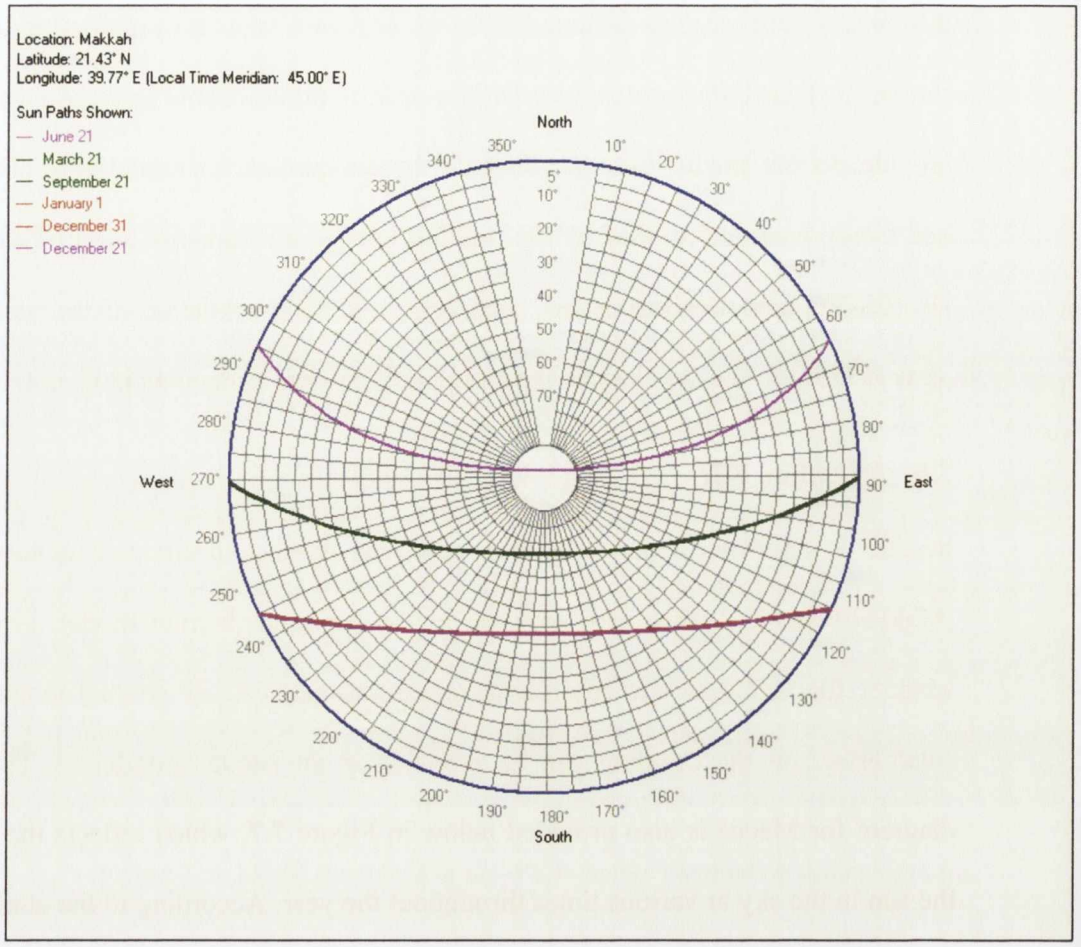


Figure 7 . 7: Generated sun path diagrams for Mecca

Figure 7.8 represents the outside air temperature used for wet and dry temperatures throughout the year as extracted from the energy model. It is used in the analysis within the model to calculate the cooling load throughout the year. Additionally, Figure 7.9 is the site orientation, which shows north direction and solar azimuth at a day in January for illustration.

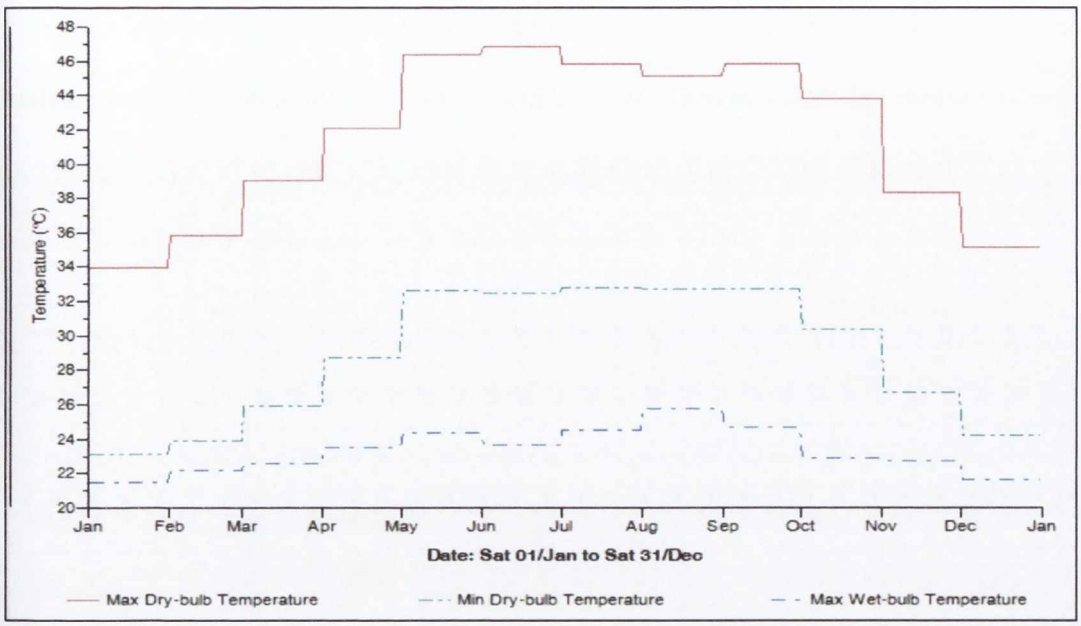


Figure 7 . 8: Outside Air Temperature

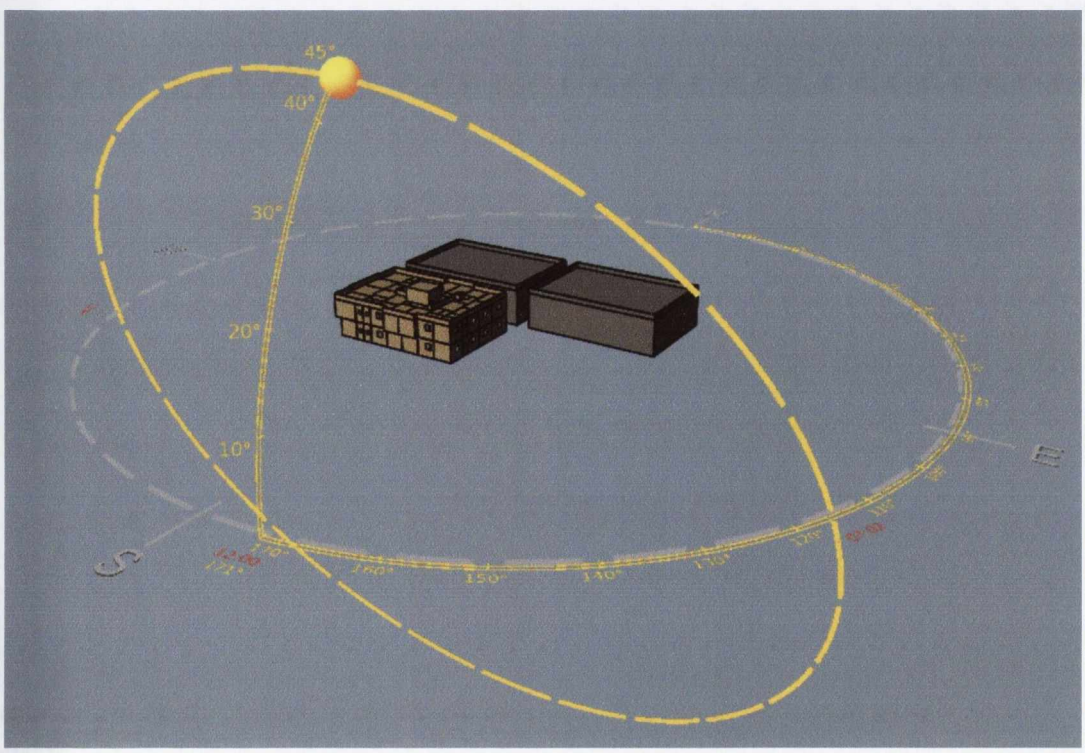


Figure 7 . 9: Site Orientation showing north direction and solar azimuth at a day in January

7.7. U-Values of the Existing Building Fabric

The existing materials were entered into the building's thermal model in order to calculate its thermal performance (table 7.3). The software generated the U-values automatically. The U-values were recalculated manually using the equations 7.1 A and B below:

$$U = \frac{1}{\Sigma R}$$

A)

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

B)

Equation 7. 1: U- Value calculation

Where:

- R is the thermal resistance of the material (m^2 K /W)
- d is the thickness of the material (m)
- λ is the thermal conductivity of the material (W/m K)

The manual recalculation of the U-values showed similar results to the ones generated by the software. Therefore, the U-values generated automatically by the software were used in this research as presented in Table 7.3.

Material Density	Thickness mm	Density kg/m^3	Conductivity W/m K
(A) Ground floor, including earth layer (U-Value: 2.01 W/m^{2}K)			
Ceramic tiles	25	2300	1.3
Mortar	25	2162	0.88
Sandstone	100	2200	1.83
Reinforced concrete	100	2300	2.3
Asphalt insulation	5	2100	0.7
Concrete high density	50	2400	2
Base-course stone	150	2000	1.4
Earth	2	1460	1.28
(B) External walls from outside to inside (U-Value: 0.72 W/m^{2}K)			
Plaster (dense)	20	1300	0.5
Concrete blocks	200	600	0.19
Plaster (light)	25	600	0.16
(C) Internal partitions (U-Value: 0.91 W/m2K)			
Plaster (light)	25	600	0.16
Concrete blocks	100	600	0.19
Plaster (light)	25	600	0.16
(D) Intermediate floors (U-Value: 1.21 W/m2K)			
Ceramic tiles	30	2300	1.3
Mortar	25	2162	0.88
Sand stone	50	2200	1.83
Reinforced concrete	120	2300	2.3
Concrete blocks	250	900	0.25
Plaster (dense)	20	1300	0.5
(E) Roof (U-Value: 0.9 W/m^{2}K)			
Ceramic tiles	20	2300	1.3
Mortar	10	2162	0.88
Sand stone	50	2200	1.83
Asphalt insulation	5	2100	0.7
Reinforced concrete	150	2300	2.3
Concrete blocks	200	900	0.25
Plaster (dense)	20	1300	0.5

Table 7 . 3: Calculated U-Value of ground floor, external walls, patrition walls, and roof

7.8. Glazing

The existing windows are single glazed with a U-value of 5.5 W/m^2K. After calculating the U-value of the existing glazing, an alteration was made in the developed model to introduce triple-glazing widows in order to improve the energy efficiency of the building. The results compared with the existing single-glazed building showed a major improvement and these details will be discussed later in this chapter.

7.9. Cooling system

Split cooling air conditioning was assigned in the software to all rooms within the building as this is the cooling system currently used in the building. A system seasonal energy efficiency ratio (SEER) of 2.98 was assigned as the efficiency of the system. This is a defined ratio by the Air Conditioning, Heating, and Refrigeration Institute in its 2008 standard AHRI 210/240, which is similar to the European seasonal energy efficiency ratio (ESEER). It is a typical value, as a lower value would require more energy for air conditioning as more energy is consumed to meet the cooling demand. The seasonal efficiency is important as it has a direct effect on the energy consumed by the air conditioning system.

7.10. Simulation Results for the Existing Building

Table 7.4 provides the cooling energy consumed to meet the demand of the existing building represented in both megawatt hours (MWh) and kilowatt hours (kWh). The table below shows that the building needs about 74,187.6 kWh per year for cooling energy. These calculations are software generated with a 24° C as an internal temperature for all calculation from now on. A building internal temperature of 24 degrees was used as recommended by the Chartered Institute of Building Service Engineers Guidance Document A, 2015.

Cooling Energy (Existing Building)		
	(MW/h)	(KW/h)
Jan 01-31	0.0101	10.1
Feb 01-28	0.0496	49.6
Mar 01-31	1.0241	1024.1
Apr 01-30	4.2222	4222.2
May 01-31	9.5361	9536.1
Jun 01-30	12.3577	12357.7
Jul 01-31	13.7613	13761.3
Aug 01-31	13.8197	13819.7
Sep 01-30	10.5008	10500.8
Oct 01-31	7.1571	7157.1
Nov 01-30	1.7228	1722.8
Dec 01-31	0.026	26
Annual Total	**74.1876**	**74,187.6**

Table 7 . 4: Cooling Energy Demand for Existing Condition to Maintain Internal Temarature at 24^{o} C

In addition, Table 7.5 below provides the electricity required to meet this building's existing energy demand as a whole. This consumption includes the electricity required for air-conditioning and associated auxiliary energy from controls, pumps and fans. It is also represented in both megawatt hours (MWh) and kilowatt hours (MWh).

Entire System Electricity (Existing Building)		
	(MW/h)	(KW/h)
Jan 01-31	0.014	14
Feb 01-28	0.0685	68.5
Mar 01-31	1.4132	1413.2
Apr 01-30	5.8266	5826.6
May 01-31	13.1598	13159.8
Jun 01-30	17.0536	17053.6
Jul 01-31	18.9906	18990.6
Aug 01-31	19.0711	19071.1
Sep 01-30	14.4912	14491.2
Oct 01-31	9.8769	9876.9
Nov 01-30	2.3775	2377.5
Dec 01-31	0.0359	35.9
Annual Total	**102.3788**	**102,378.8**

Table 7 . 5: Entire System Electricity Required for Existing Building

Figure 7.10 below represents the day in which the peak-cooling load is required based on the annual weather profile, which occurs on the 4th of August. The peak-cooling load is 65 kW. In addition, Figure 7.11 and Table 7.6 below highlights the amount of carbon emissions produced from the air conditioning system for the existing condition.

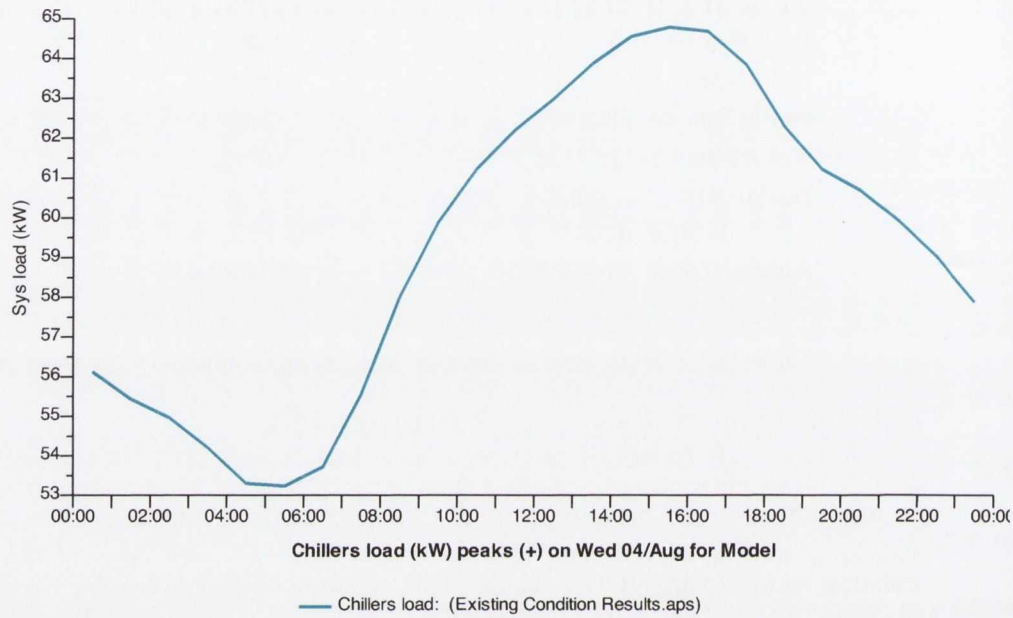


Figure 7 . 10: Annual Peak Load for Existing Building

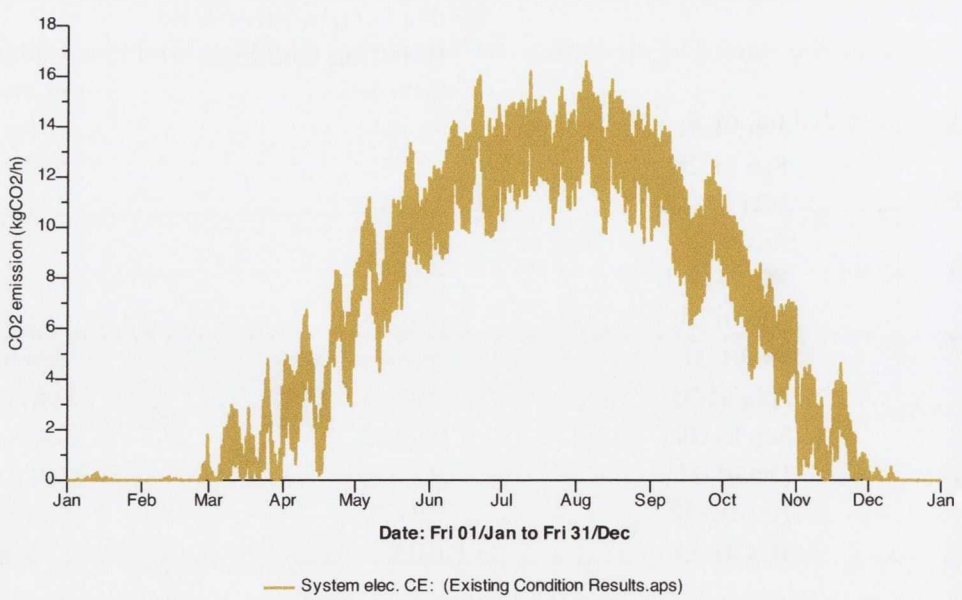


Figure 7 . 11: Yearly Amount of Carbon Emissions in Existing Building

	Carbon Emissions ($kgCO_2$) (Existing Building)
Jan 01-31	7
Feb 01-28	36
Mar 01-31	733
Apr 01-30	3024
May 01-31	6830
Jun 01-30	8851
Jul 01-31	9856
Aug 01-31	9898
Sep 01-30	7521
Oct 01-31	5126
Nov 01-30	1234
Dec 01-31	19
Annual Total	**53,135**

Table 7 . 6: Carbon Emissions Arising from the Electricity Consumption of the Exisitng Building

7.11. Solar Photovoltaic

A monocrystalline photovoltaic installation was applied to the building thermal model to determine the energy and CO_2 savings achievable. A panel area of 450 m^2 (Approx. 75% of roof area) was applied to the building model. The panels were assigned to be south facing with an inclination of 30 degrees from horizontal. This is typical for standard installation of PVs to maximize performance and optimize irradiance received from the sun. The properties of the panels (derived from the building model) are provided below in figure 7.12.

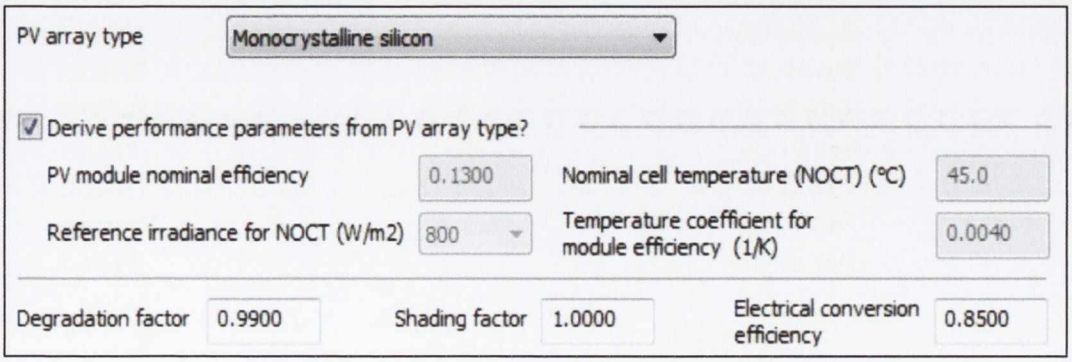


Figure 7 . 12: Properties of the Panels Derived From the Building Model and Inputs

Figure 7.13 shows the performance of the PV installation over the simulation year (shown as a minus value) and Table 7.7 the energy produced from the PV installation in the simulation year. As it can be seen, 83,257 kWh are produced by the PVs resulting in a reduction of 83,257 kWh in building annual grid energy use.

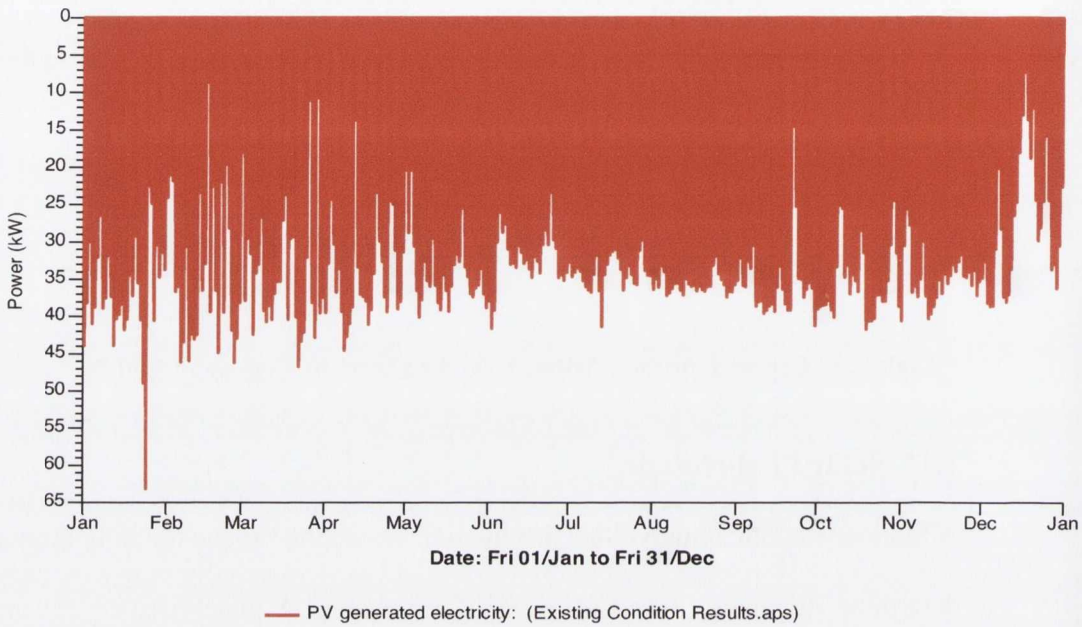


Figure 7 . 13: Performance of the PVs Installation Over the Simulation Year

PVs' Total Generated Electricity		
	(MW/h)	**(kW/h)**
Jan 01-31	7.053	7053
Feb 01-28	6.06	6060
Mar 01-31	6.898	6898
Apr 01-30	6.7563	6756.3
May 01-31	7.669	7669
Jun 01-30	7.1928	7192.8
Jul 01-31	7.6356	7635.6
Aug 01-31	8.0036	8003.6
Sep 01-30	7.117	7117
Oct 01-31	7.1643	7164.3
Nov 01-30	6.5803	6580.3
Dec 01-31	5.128	5128
Annual Total	**83.2579**	**83,257.9**

Table 7 . 7: Total Energy Production from the PVs Installation in the Simulation Year

Based on the solar irradiance calculation within the software, the day in which the PVs will have the highest output will be on Friday the 1st January with a peak of approximately 45kW PVs generated electricity (Figure 7.14). However, Figure 7.15 shows the reduction in carbon emissions due to the use of the PVs installation over the simulation year. It is also shown as a minus value as it represents displacing of carbon emissions. Table 7.8 highlights the total carbon emissions amount reduced monthly after PV installation. The total reduction amount is 43,211 $kgCO_2$ annually.

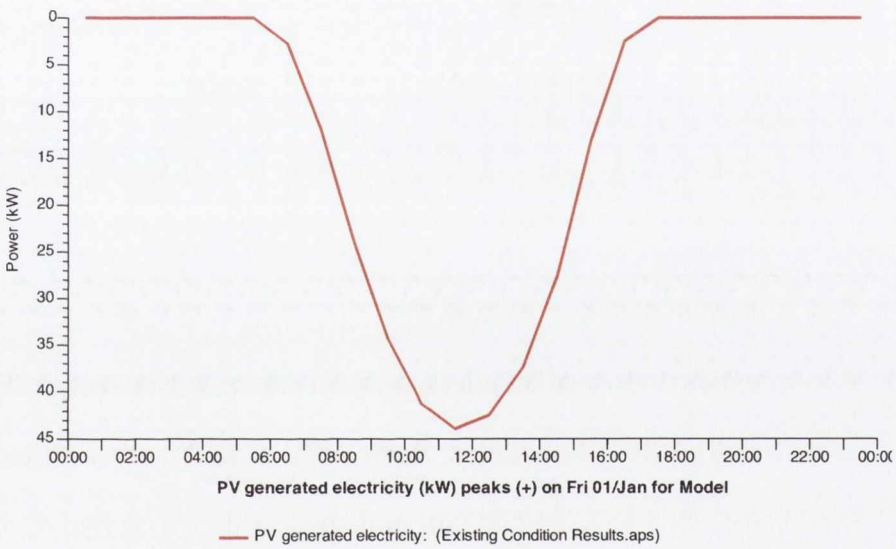


Figure 7 . 14: PVs Annual Peak Electricity Generation

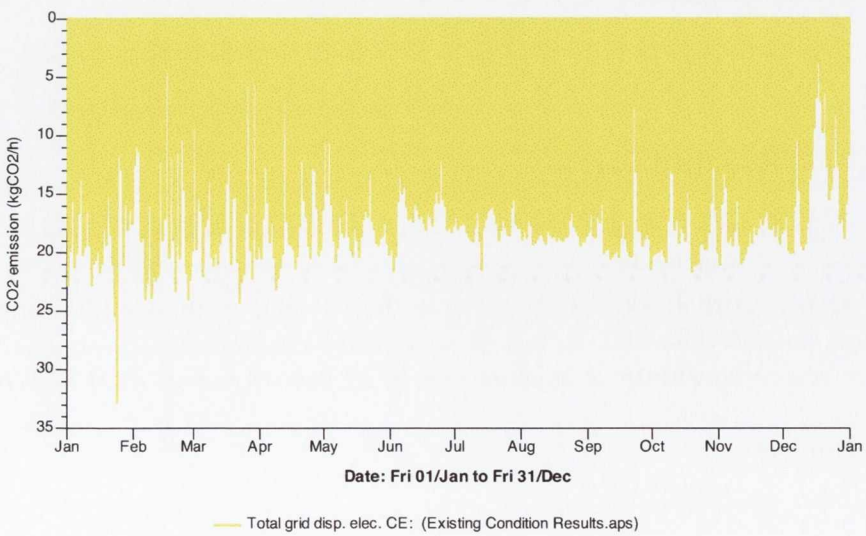


Figure 7 . 15: Total Grid Reduction of Carbon Emissions

Grid Reduction of Carbon Emissions ($kgCO_2$)	
Date	
Jan 01-31	3661
Feb 01-28	3145
Mar 01-31	3580
Apr 01-30	3507
May 01-31	3980
Jun 01-30	3733
Jul 01-31	3963
Aug 01-31	4154
Sep 01-30	3694
Oct 01-31	3718
Nov 01-30	3415
Dec 01-31	2661
Annual Total	**43,211**

Table 7 . 8: Monthly and Yearly Grid Reduction of Carbon Emissions Using PVs

7.11.1. Cost of Monocrystalline PVs

According to current market prices, the total cost of the monocrystalline PVs would cost about 46,062 USD. In addition, the total installed system of a total area of 450 m2 would cost about 133,294 USD for grid-connected PVs on roof (Centre for Alternaive Technology, 2016). In this regard, more discussion could be found later in the discussion section.

7.12. Rammed Earth

The existing external wall was replaced with an insulated rammed earth wall with the properties in Table 7.9. As a result, the U-Value of the wall has improved dramatically when compared to the existing case (0.29 W/m^2K versus the 0.72 W/m^2K of the existing building).

Material (Outside to Inside)	Thickness mm	Conductivity W/(m-k)	Density Kg/m^3	Specific Heat Capacity J/(kg-k)
Rammed Earth	250.0	1.2500	1540.0	1260.0
Mineral Fibre Wool	100.0	0.0350	30.0	1000.0
Rammed Earth	250.0	1.2500	1540.0	1260.0

Table 7 . 9: Details of Insulated Rammed Earth Walls

The total thickness of the proposed wall is 600 mm (24 inches). This is a practical thickness and a structural sandwich wall system that has been tested and constructed by SIREWALL Inc. in Canada. Although this is an increase in the current standards wall thickness, it is ideal in terms of energy efficiency and building thermal insulation. In fact, historic buildings had adopted similar wall thicknesses in dwellings and other types of buildings. In addition, Saudi Arabia has abundances in land, in which, the increase in the wall thickness should not be an issue. However, this may result in more costs and material consumption along with the need for construction workmanship.

Moreover, mineral wool fiber insulation is one of the types of insulation materials typically used in rammed earth structures both in Canada and the United States (Windstorm and Schmidt, 2013). According to same source, it has an R-value of 4.3/in. and a density of 3.4 lbs/ft^3 (0.05 g/cm^3). This type of insulation is designed for use in a masonry wall cavity. When mineral wool fiber insulation is used interstitially in a rammed earth wall (Figure 7.16) it is prone to compression during the ramming process. It also may suffer some reduction in thermal performance as a result of ramming process (Windstorm and Schmidt, 2013).

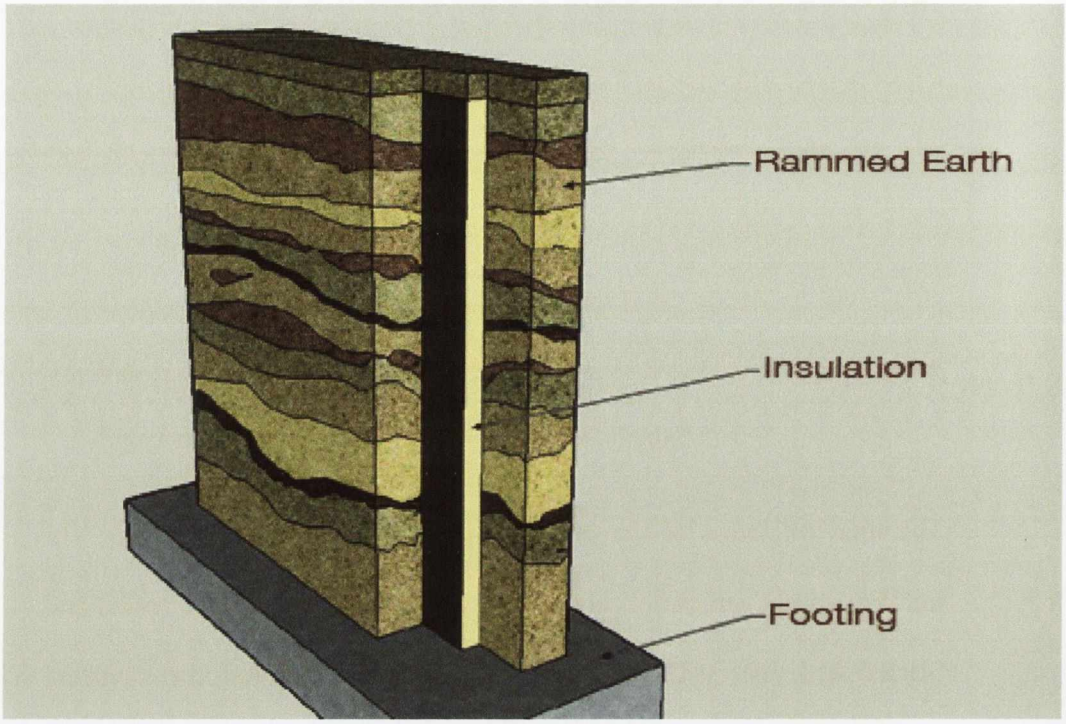


Figure 7 . 16: Rammed Earth Walls with Sandwiched Insulation

(http://www.rammedearth.info)

The effect of replacing the existing walls with rammed earth walls on energy consumption and CO_2 emissions is provided in the following tables and charts. Table 7.10 shows the cooling energy required with rammed earth walls while Table 7.11 shows the electricity required to meet cooling demand for the building with the insulated rammed earth walls. Figure 7.17 illustrates the peak cooling load of 59 kW with insulated rammed earth walls on 4th of August (peak heat). Additionally, Table 7.12 shows the annual carbon emissions from system air conditioning with insulated rammed earth walls. Discussions later on this chapter will show the benefits of applying these sustainable technologies.

Earth is a porous and hygroscopic material that contains active clay minerals, therefore earth walls absorb water vapour from the air when relative humidity increases and this moisture is released once the humidity falls. As it is usual practice to leave earth walls exposed to the interior, the availability of combined thermal and hygric buffering acting

as passive air conditioning is maximized when compared with other materials such as brick or concrete (Hall and Allinson, 2009). This should avoid decay by moisturize of the sandwiched mineral wool insulation.

Cooling Energy (Rammed Earth Insulated Wall)		
	(MW/h)	**(kW/h)**
Jan 01-31	0.0116	11.6
Feb 01-28	0.0452	45.2
Mar 01-31	1.1442	1144.2
Apr 01-30	4.0931	4093.1
May 01-31	8.8804	8880.4
Jun 01-30	11.416	11416
Jul 01-31	12.7199	12719.9
Aug 01-31	12.7749	12774.9
Sep 01-30	9.7819	9781.9
Oct 01-31	6.8009	6800.9
Nov 01-30	1.8677	1867.7
Dec 01-31	0.0503	50.3
Annual Total	**69.5861**	**69,586.1**

Table 7 . 10: Cooling Energy Required with Rammed Earth External Walls to Mainatain the Interior at 24 °C

Entire System Electricity Requirment (Rammed Earth Insulated Wall)		
	(MW/h)	**(kW/h)**
Jan 01-31	0.016	16
Feb 01-28	0.0623	62.3
Mar 01-31	1.5789	1578.9
Apr 01-30	5.6485	5648.5
May 01-31	12.2549	12254.9
Jun 01-30	15.7541	15754.1
Jul 01-31	17.5535	17553.5
Aug 01-31	17.6294	17629.4
Sep 01-30	13.499	13499
Oct 01-31	9.3853	9385.3
Nov 01-30	2.5775	2577.5
Dec 01-31	0.0694	69.4
Annual Total	**96.0288**	**96,028.8**

Table 7 . 11: Electricity Required to Meet Cooling Demand with Rammed Earth Walls

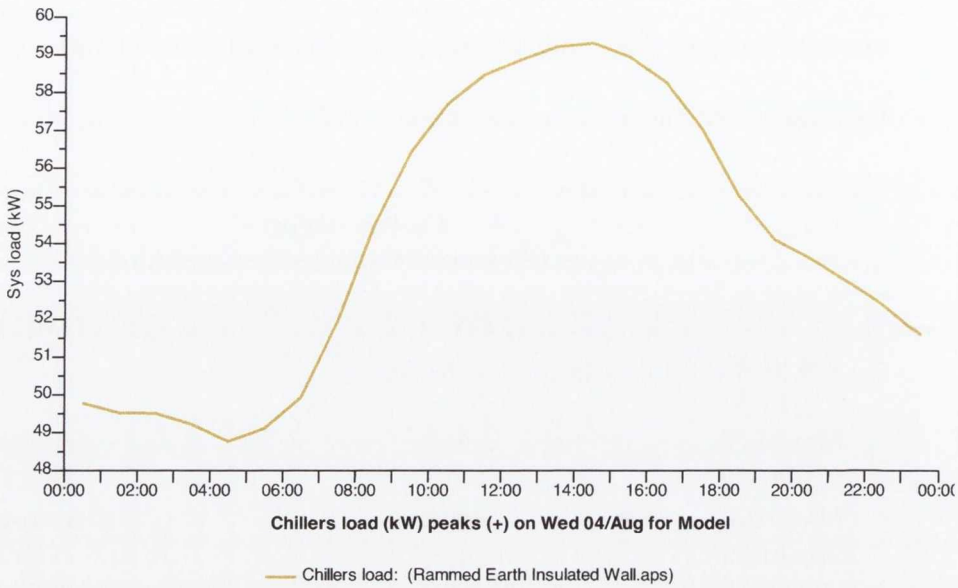


Figure 7 . 17: Peak Cooling Load of 59 kW with Insulated Rammed Earth Walls

Carbon Emissions ($kgCO_2$) (Rammed Earth Insulated Wall)	
Jan 01-31	8
Feb 01-28	32
Mar 01-31	819
Apr 01-30	2932
May 01-31	6360
Jun 01-30	8176
Jul 01-31	9110
Aug 01-31	9150
Sep 01-30	7006
Oct 01-31	4871
Nov 01-30	1338
Dec 01-31	36
Annual Total	**49839**

Table 7 . 12: Annual carbon emissions from air conditioning with rammed earth wall

7.12.1. Cost of Rammed Earth

The cost of existing walls would be 850 Saudi Riyal (226 USD) per vertical square meter according to current prices. However, the cost associated with rammed earth is estimated at 250 USD for a vertical square meter of rammed earth with 300 mm

thickness according to international markets. Consequently, with total external wall areas of 792 m^2, the total cost would be 334,500 USD. The advantage of using this technique is the fact that stabilized rammed earth does not need interior or exterior finishing which can reduce costs of construction (The Constructor, 2016). A further discussion on this regard could be found later on the discussion section.

7.13. Thermally Insulated Cavity Wall

In order to investigate further options, the existing external walls were replaced with insulated cavity walls with the properties in Table 7.13 as another proposed scenario. It was noted that the U-Value lowered to 0.35 W/m^2K improving the existing value (0.72 W/m^2K). However, the insulated rammed earth walls scenario provided a lower value of 0.29 W/m^2K (Table 7.9).

Material (Outside to Inside)	Thickness mm	Conductivity W/(m-k)	Density Kg/m^3	Specific Heat Capacity J/(kg-k)
Gypsum Plastering	15.0	0.4200	1200.0	837.0
Concrete Block	100.0	0.8400	1700.0	800.0
Cavity	50.0	-	-	-
Mineral Fibre Wool	75.0	0.0350	30.0	1000.0
Concrete Block (Medium)	100.0	0.5100	1400.0	1000.0
Gypsum Plastering	15.0	0.4200	1200.0	837.0

Table 7 . 13: Details of the Proposed Thermally Insulated Cavity Wall

The proposed wall thickness is based on the recommended "best practice" provided by many professionals in Saudi Arabia. The effect of replacing the existing external concrete block walls with mineral wool insulated cavity wall on energy and CO_2 emissions is documented in the following tables and charts. Benefits gained by applying this sustainable technology are discussed below.

Cooling Energy (Mineral Wool Cavity Wall)		
	(MW/h)	(kW/h)
Jan 01-31	0.0129	12.9
Feb 01-28	0.0582	58.2
Mar 01-31	1.1376	1137.6
Apr 01-30	4.1316	4131.6
May 01-31	8.9831	8983.1
Jun 01-30	11.554	11554
Jul 01-31	12.8585	12858.5
Aug 01-31	12.9107	12910.7
Sep 01-30	9.8619	9861.9
Oct 01-31	6.8208	6820.8
Nov 01-30	1.8165	1816.5
Dec 01-31	0.0413	41.3
Annual Total	**70.187**	**70,187**

Table 7 . 14: Cooling Energy Required for Mineral Wool Cavity Wall

Entire System Electricity (Mineral Wool Cavity Wall)		
	(MW/h)	(kW/h)
Jan 01-31	0.0178	17.8
Feb 01-28	0.0803	80.3
Mar 01-31	1.5699	1569.9
Apr 01-30	5.7016	5701.6
May 01-31	12.3966	12396.6
Jun 01-30	15.9445	15944.5
Jul 01-31	17.7447	17744.7
Aug 01-31	17.8167	17816.7
Sep 01-30	13.6095	13609.5
Oct 01-31	9.4127	9412.7
Nov 01-30	2.5068	2506.8
Dec 01-31	0.0569	56.9
Annual Total	**96.8581**	**96,858.1**

Table 7 . 15: Electricity Required for Air Conditioning (Entire System) for Mineral Wool Cavity Wall

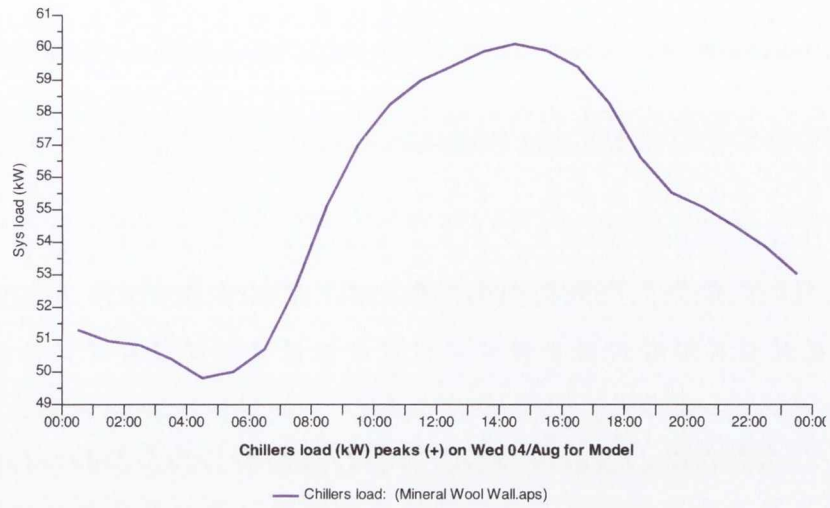


Figure 7 . 18: Peak Cooling Load: 60.1 kW for Mineral Wool Cavity Wall

Carbon Emissions ($kgCO_2$) (Mineral Cavity Wool Wall)	
Date	
Jan 01-31	9
Feb 01-28	42
Mar 01-31	815
Apr 01-30	2959
May 01-31	6434
Jun 01-30	8275
Jul 01-31	9209
Aug 01-31	9247
Sep 01-30	7063
Oct 01-31	4885
Nov 01-30	1301
Dec 01-31	30
Annual Total	**50,269**

Table 7 . 16: Total Carbon Emissions from Air Conditioning for Mineral Wool Cavity Wall

7.13.1. Cost of Cavity Wall

The cavity wall would cost about 226 USD per vertical square meter of the current thickness of 100 mm in the market. Consequently, the total cost of the total external wall area of 792 m^2 with two walls of 100 mm each would cost approximately 358,000 USD.

However, the cost would increase due to exterior and interior finishing. A further discussion on this regard could be found later on the discussion section.

7.13.2. Cost of Mineral Wool Insulation

The Knauf Mineral Wool Insulation used in the simulation costs about 9.2 USD per square meter. Consequently, the total external walls of about 792 m^2 would cost approximately 7,286 USD.

7.14. Rammed Earth Wall, Triple Glazing and Insulated Roof

In order to add more efficient and sustainable principles to the proposed solutions, new other scenarios are proposed using triple glazed windows and roof insulation. In this scenario, triple glazing with U-Value of 1.3 W/m^2K is used to replace the original single glazed windows (U-value: 5.5 W/m^2K).

The selection of this type of glazing is based on some facts. These include the wide availability of this type of glazing which is manufactured locally. It includes a great U-value compared to other types of windows. In addition, this type of glazing offers a significant reduction in noise pollution, which is ideal for those living in noisy areas like Mecca. Triple glazed windows also provide security and privacy as well as working as a thermal insulator, which is very needed in hot weathers like in Saudi Arabia.

7.14.1. Cost of Triple Glazing

The triple glazed windows would cost about 97 to 176 USD per square meter according to the market prices as of the fourth quarter of 2016. The averaged cost would be 137 USD per square meter, in which, it would cost about 10,034 USD for the 58 m^2 of the total glazed area of the building.

7.14.2. Roof Insulation

In addition, a 75 millimeters of mineral wool insulation was added to existing case roof (Table 7.3-E) in order to reach more efficient results. As a result, the U-value improved

to 0.3 W/m^2K versus 0.9 W/m^2K of the base case. The thermal insulation can be applied below the top floor ceiling and above the dropped ceiling (a secondary ceiling that hangs below the main structural ceiling). This is the way of insulating existing buildings' roofs in current Saudi Arabian practices.

Table 7.17 shows the energy required for cooling the building where rammed earth walls, triple glazing and a mineral wool insulated roof are used. It also shows the electricity required to meet the entire building cooling demand when using these sustainable features. The electricity values include air conditioning and associated energy (controls, pumps and fans).

In addition, Table 7.18 shows the total carbon emissions produced by the building where rammed earth walls, triple glazing and mineral wool roof insulation are used. As it can be seen, the carbon emissions lower by 10,578 $kgCO_2$ annually when compared to the existing building (53,135 $kgCO_2$).

Entire Cooling System Electricity
(Rammed Earth, Triple Glazing, and Insulated Roof)

	(MW/h)	(kW/h)
Jan 01-31	0.0467	46.7
Feb 01-28	0.1468	146.8
Mar 01-31	1.6785	1678.5
Apr 01-30	4.9797	4979.7
May 01-31	10.2712	10271.2
Jun 01-30	13.117	13117
Jul 01-31	14.6228	14622.8
Aug 01-31	14.6695	14669.5
Sep 01-30	11.4258	11425.8
Oct 01-31	8.1519	8151.9
Nov 01-30	2.6347	2634.7
Dec 01-31	0.253	253
Annual Total	**81.9975**	**81,997.5**

Table 7 . 17: System Electricity Required for Entire Cooling System of the Building with Rammed Earth Walls, Triple Glazing and Insulated Roof

Carbon Emissions ($kgCO_2$) (Rammed Earth, Triple Glazing, and Insulated Roof)	
Jan 01-31	24
Feb 01-28	76
Mar 01-31	871
Apr 01-30	2584
May 01-31	5331
Jun 01-30	6808
Jul 01-31	7589
Aug 01-31	7613
Sep 01-30	5930
Oct 01-31	4231
Nov 01-30	1367
Dec 01-31	131
Annual Total	**42557**

Table 7 . 18: System Electricity Carbon Emissions with Rammed Earth Walls, Triple Glazing, and Insulated Roof

7.15. Mineral Wool Cavity Wall, Triple Glazing and Insulated Roof

Table 7.19 shows the energy required for cooling the building where cavity walls, triple glazing and a mineral wool insulated roof are used. It also shows the electricity required to meet the building cooling demand with these features. Table 7.20 shows the total carbon emissions produced by this building. As it can be seen, emissions are lowered by 10,161 $kgCO_2$ annually when compared with the current building.

Entire Cooling System Electricity (Mineral Wool Cavity Wall, Triple Glazing, and Insulated Roof)		
	(MW/h)	**(KW/h)**
Jan 01-31	0.0488	48.8
Feb 01-28	0.1438	143.8
Mar 01-31	1.6567	1656.7
Apr 01-30	5.0291	5029.1
May 01-31	10.4164	10416.4
Jun 01-30	13.3137	13313.7
Jul 01-31	14.824	14824
Aug 01-31	14.8659	14865.9
Sep 01-30	11.5447	11544.7
Oct 01-31	8.1858	8185.8
Nov 01-30	2.5622	2562.2
Dec 01-31	0.2112	211.2
Annual Total	**82.8022**	**82802.2**

Table 7 . 19: Entire System Electricity Required for Cooling the Building with Mineral Wool Cavity Wall, Triple Glazing and Insulated Roof

Carbon Emissions ($kgCO_2$) (Mineral Wool Cavity Wall, Triple Glazing, and Insulated Roof)	
Jan 01-31	25
Feb 01-28	75
Mar 01-31	860
Apr 01-30	2610
May 01-31	5406
Jun 01-30	6910
Jul 01-31	7694
Aug 01-31	7715
Sep 01-30	5992
Oct 01-31	4248
Nov 01-30	1330
Dec 01-31	110
Annual Total	**42974**

Table 7 . 20: System Electricity Carbon Emissions with Mineral Wool Cavity Wall, Triple Glazing and Insulated Roof

7.16. Comparison with existing building and Discussion

7.16.1. Cooling Energy Comparison

By using external rammed earth walls, mineral wool insulation in the roof and triple glazing, there is an annual reduction of 4,601 kWh in the energy required for cooling the building. In addition, by using solar PVs, the building's energy requirements can be reduced by a further 83,357.9 kWh with a total reduction over the existing condition of 87,859.4 kWh per year (Table 7.21).

Date	Rammed Earth Wall, Triple Glazing, and Insulated Roof Cooling Energy (kWh)	Existing Condition Cooling Energy (kWh)	Reduction in Cooling Energy (kWh)	Power Generated From PVs (kWh)
Jan 01-31	11.6	10.1	-1.5	7053
Feb 01-28	45.2	49.6	4.4	6060
Mar 01-31	1144.2	1024.1	-120.1	6898
Apr 01-30	4093.1	4222.2	129.1	6756.3
May 01-31	8880.4	9536.1	655.7	7669
Jun 01-30	11416	12357.7	941.7	7192.8
Jul 01-31	12719.9	13761.3	1041.4	7635.6
Aug 01-31	12774.9	13819.7	1044.8	8003.6
Sep 01-30	9781.9	10500.8	718.9	7117
Oct 01-31	6800.9	7157.1	356.2	7164.3
Nov 01-30	1867.7	1722.8	-144.9	6580.3
Dec 01-31	50.3	26	-24.3	5128
Annual total	**69586.1**	**74187.6**	**4601.5**	**83257.9**
Reduction of Grid Electricity with PVs, Rammed Earth, Triple Glazing, and Insulated Roof:			**87,859.4 kWh per Year**	

Table 7 . 21: Comparison of the Cooling Energy of the Existing Building with a Building Featuring Rammed Earth Wall, Triple Glazing and Insulated Roof

On the other hand, using a mineral wool cavity wall, mineral wool insulation to the roof and triple glazing delivers an annual reduction of 4,006.6 kWh in the energy required for cooling the building. Additionally, using solar PVs, the buildings energy can be reduced by a further 83,357.9 kWh with a total reduction/improvement over the existing condition of 87,258.5 kWh per year (Table 7.22).

Date	Insulated Cavity Wall, Triple Glazing and insulated Roof Cooling Energy (kWh)	Existing Condition Cooling Energy (kWh)	Reduction in Cooling Energy (kWh)	Power Generated From PVs (kWh)
Jan 01-31	12.9	10.1	-2.8	7053
Feb 01-28	58.2	49.6	-8.6	6060
Mar 01-31	1137.6	1024.1	-113.5	6898
Apr 01-30	4131.6	4222.2	90.6	6756.3
May 01-31	8983.1	9536.1	553	7669
Jun 01-30	11554	12357.7	803.7	7192.8
Jul 01-31	12858.5	13761.3	902.8	7635.6
Aug 01-31	12910.7	13819.7	909	8003.6
Sep 01-30	9861.9	10500.8	638.9	7117
Oct 01-31	6820.8	7157.1	336.3	7164.3
Nov 01-30	1816.5	1722.8	-93.7	6580.3
Dec 01-31	41.3	26	-15.3	5128
Annual total	**70187**	**74187.6**	**4000.6**	**83257.9**
Reduction of Grid Electricity with PVs, Insulated Cavity Wall, Triple Glazing and insulated Roof:			**87,258.5** kWh per Year	

Table 7 . 22: Cooling Energy of Existing building compared with a Building Featuring Insulated Cavity Wall, Triple Glazing and Insulated Roof

The compared results in tables 7.21 and 7.22 are similar due to the fact that these two scenarios are the top scenarios in performance among all other simulated scenarios. The purpose of these tables is to show and compare each scenario separately with the existing base case for clarification of results and to show the impact with and without

the power generated from the PVs. However, tables 7.23 and 7.24 are the same but for the entire cooling system.

7.16.2. Entire System Electricity Comparison

By adopting a rammed earth wall, mineral wool insulation to the roof and triple glazing, there is an annual reduction of 20,381.3 kWh in the entire electricity required for cooling (this includes electricity for air conditioning and heat rejection and pumps associated with the air conditioning system). In addition, using solar PVs the building electricity requirement can be reduced by a further 83,357.9 kWh with a total reduction/improvement over the existing condition of 103639.2 kWh per year. In this case, the PVs covers more that the need for cooling the building (Table 7.23).

Date	Rammed Earth Wall, Triple Glazing and insulated Roof Cooling Electricity (kWh)	Existing Condition Cooling Electricity (kWh)	Reduction in Cooling Electricity (kWh)	Power Generated From PVs (kWh)
Jan 01-31	46.7	14	32.7	7053
Feb 01-28	146.8	68.5	78.3	6060
Mar 01-31	1678.5	1413.2	265.3	6898
Apr 01-30	4979.7	5826.6	846.9	6756.3
May 01-31	10271.2	13159.8	2888.6	7669
Jun 01-30	13117	17053.6	3936.6	7192.8
Jul 01-31	14622.8	18990.6	4367.8	7635.6
Aug 01-31	14669.5	19071.1	4401.6	8003.6
Sep 01-30	11425.8	14491.2	3065.4	7117
Oct 01-31	8151.9	9876.9	1725	7164.3
Nov 01-30	2634.7	2377.5	257.2	6580.3
Dec 01-31	253	35.9	217.1	5128
Annual total	**81997.5**	**102378.8**	**20381.3**	**83257.9**
Reduction of Grid Electricity with PVs, Rammed Earth, Triple Glazing and insulated Roof:				**103,639.2 kWh per Year**

Table 7 . 23: Comparison of the Cooling System Electricity of the Existing Building with a Building Featuring Rammed Earth Wall, Triple Glazing and Insulated Roof

A mineral wool cavity wall, mineral wool insulation to the roof and triple glazing lead to an annual reduction of 19,576.6 kWh in the electricity required for cooling. Additionally, using solar PVs the building's electricity can be reduced by a further 83,357.9 kWh with a total reduction/improvement over the existing condition of 102,834.5 kWh per year. In this case, the power generated by the PVs surpasses what is needed for cooling (Table 7.24).

Date	Insulated Cavity Wall, Triple Glazing and insulated Roof Cooling Electricity (kWh)	Existing Condition Cooling Electricity (kWh)	Reduction in Cooling Electricity (kWh)	Power Generated From PVs (kWh)
Jan 01-31	48.8	14	-34.8	7053
Feb 01-28	143.8	68.5	-75.3	6060
Mar 01-31	1656.7	1413.2	-243.5	6898
Apr 01-30	5029.1	5826.6	797.5	6756.3
May 01-31	10416.4	13159.8	2743.4	7669
Jun 01-30	13313.7	17053.6	3739.9	7192.8
Jul 01-31	14824	18990.6	4166.6	7635.6
Aug 01-31	14865.9	19071.1	4205.2	8003.6
Sep 01-30	11544.7	14491.2	2946.5	7117
Oct 01-31	8185.8	9876.9	1691.1	7164.3
Nov 01-30	2562.2	2377.5	-184.7	6580.3
Dec 01-31	211.2	35.9	-175.3	5128
Annual total	**82802.2**	**102378.8**	**19576.6**	**83257.9**
Reduction of Grid Electricity with PVs, Insulated Cavity Wall, Triple Glazing and insulated Roof:			**102,834.5 kWh per Year**	

Table 7 . 24: Comparison of the Cooling System Electricity of the Existing Building with a Building Featuring Insulated Cavity Wall, Triple Glazing and Insulated Roof

7.16.3. Carbon Emissions Comparison

The rammed earth walls, mineral wool insulation to the roof and triple glazing lead to an annual reduction of 10,578 kgCO2 in the carbon emission required for cooling. In addition, using solar PVs the buildings carbon emissions can be reduced by a further 43,211 kgCO2 with a total reduction of 53,789 kgCO2 per year when compared with the existing building (Table 7.25).

Date	**Electricity Carbon Emissions ($kgCO_2$) (Cooling System)**		**CO_2 Reduction Using PVs ($kgCO_2$)**	**Total CO_2 Reduction ($kgCO_2$)**
	CO_2 Emission of Existing Condition	CO_2 Emission of Rammed Earth Triple Glazing, and Insulated Roof		
Jan 01-31	7	24	3661	3644
Feb 01-28	36	76	3145	3105
Mar 01-31	733	871	3580	3442
Apr 01-30	3024	2584	3507	3947
May 01-31	6830	5331	3980	5479
Jun 01-30	8851	6808	3733	5776
Jul 01-31	9856	7589	3963	6230
Aug 01-31	9898	7613	4154	6439
Sep 01-30	7521	5930	3694	5285
Oct 01-31	5126	4231	3718	4613
Nov 01-30	1234	1367	3415	3282
Dec 01-31	19	131	2661	2549
Annual total	**53135**	**42557**	**43211**	**53789**
Reduction of Carbon Emissions with PVs, Rammed Earth, Triple Glazing, and Insulated Roof:			**53,789 $KgCO_2$ per Year**	

Table 7 . 25: Comparison of the Carbon Emissions of the Existing Building with a Building Featuring Rammed Earth Wall, Triple Glazing and Insulated Roof

When rammed earth is replaced with a mineral wool cavity wall, there is an annual reduction of 10,161 $kgCO_2$ in the carbon emission required for cooling. Additionally,

using solar PVs the building's carbon emissions can be reduced by a further 43,211 $kgCO_2$ with a total reduction over the existing building of 53,372 $kgCO_2$ per year. This means that the cooling system electricity would emit no carbon, generating the power needed with the solar PVs on the building's roof (Table 7.26).

Date	System Electricity Carbon Emissions ($kgCO_2$) (Cooling System)		CO_2 Reduction Using PVs ($kgCO_2$)	Total CO_2 Reduction ($kgCO_2$)
	CO_2 Emission of Existing Condition	CO_2 Emission of Mineral Wool Wall, Triple Glazing, and Insulated Roof		
Jan 01-31	7	25	3661	3643
Feb 01-28	36	75	3145	3106
Mar 01-31	733	860	3580	3453
Apr 01-30	3024	2610	3507	3921
May 01-31	6830	5406	3980	5404
Jun 01-30	8851	6910	3733	5674
Jul 01-31	9856	7694	3963	6125
Aug 01-31	9898	7715	4154	6337
Sep 01-30	7521	5992	3694	5223
Oct 01-31	5126	4248	3718	4596
Nov 01-30	1234	1330	3415	3319
Dec 01-31	19	110	2661	2570
Annual total	**53135**	**42974**	**43211**	**53372**
Reduction of Carbon Emissions with PVs, Mineral Wool Wall, Triple Glazing, and Insulated Roof:			**53,372 $KgCO_2$ per Year**	

Table 7 . 26: Comparison of the Carbon Emissions of the Existing Building with a Building Featuring Mineral Wool Wall, Triple Glazing and Insulated Roof

The figures above evidence the low dependence of the building from the electricity grid when applying the sustainable features proposed. Therefore, applying these sustainable elements to future residential (and other buildings) would carry important reduction of carbon emissions and grid-electricity consumption with the subsequent environmental and economic impact. The economic impact of such switch in electricity source is considered in the discussion below.

7.17. Discussion

Although there are some upfront costs in the application of each of proposed solutions, it is believed that some professionals consider the 3Ps (profit, people and planet) in relation to the built environment decision-making processes. For example, people's health and productivity are high in sustainable buildings compared to traditional buildings according to recent studies. This reduces the expenditure on health resulting in saving money spent on health plus providing a healthy environment. However, planet could benefit of sustainable construction in minimizing the harm of built environment on the natural environment, thus, reducing our efforts and money spending on confronting the current global warming impacts including the high temperatures, floods, drought and others.

Prior to make a decision on which scenario is the best, the simulated results were seen without the addition of the PVs power generated onsite. In economic perspective, it is cleared that the insulated rammed earth (334,500 USD) is lower in cost compared to the insulated cavity wall (358,000 USD). Additionally, the rammed earth would not need neither internal nor external finishing according to many sources and practices, which gives it more priority in application.

Thus, the cost will remain the same for rammed earth scenario, as the other scenario of insulated cavity walls would increase the cost due to the need of internal and external finishing. In general, the recommended scenario is the insulated rammed earth since the overall advantages are higher than other scenarios including lower electricity bill and carbon emissions reduction of about 25% compared to 19% of the insulated cavity wall scenario plus the fact that rammed earth is a local sustainable materials in need of reintroduction in the current and future practices.

Using either rammed earth walls or mineral wool cavity walls each with a mineral wool insulated roof and triple glazing has a significant effect on the building carbon emissions and electricity consumption for cooling the building (Figures 7.19 and 7.20). For instance, the cooling system's carbon emissions lowered by approximately 25% when applying insulated rammed earth walls, triple-glazing windows and insulated roof.

In the calculations above, there is little difference in the energy and carbon performance of the building with rammed earth walls or cavity walls although with the rammed earth wall, the performance is slightly better. Therefore, the embodied energy and carbon emissions associated with each scenario are essential to distinguish more between the two scenarios. In fact, embodied energy emissions is accounted for 10 to 20 percent of the lifecycle emissions based on a study carried out a critical review analysis of buildings (including residential and office buildings) from 73 case studies across 13 countries (Ramesh et al. 2010).

However, the embodied energy of the two scenarios was calculated based of the Inventory of Carbon & Energy (ICE) (Version 2.0) of Bath University (Hammond and Jones, 2011). The results determined that the embodied energy and embodied carbon emissions of the rammed earth is much lower than the cavity wall scenario. Table 7.27 represents these findings.

Scenario	Embodied Energy MJ/Kg	Embodied Carbon $KgCO_2/kg$
Cavity Wall	19,530.72	13,73.32
Rammed Earth	14,224.32	1,110.38

Table 7 . 27: Embodied Energy and Embodied Carbon Emissions of Both Scenarios

According to this, the rammed earth scenario would save 5,306.4 MJ/Kg on the embodied energy and approximately 263 $KgCO_2/kg$ on the embodied carbon emissions. However, further results showed that (with rammed earth scenario) there is a reduction in electricity consumption (Figure 7.19). In fact, the cooling system's carbon emissions lowered by approximately 25% when applying insulated rammed earth walls, triple-glazing windows and insulated roof (Figure 7.20).

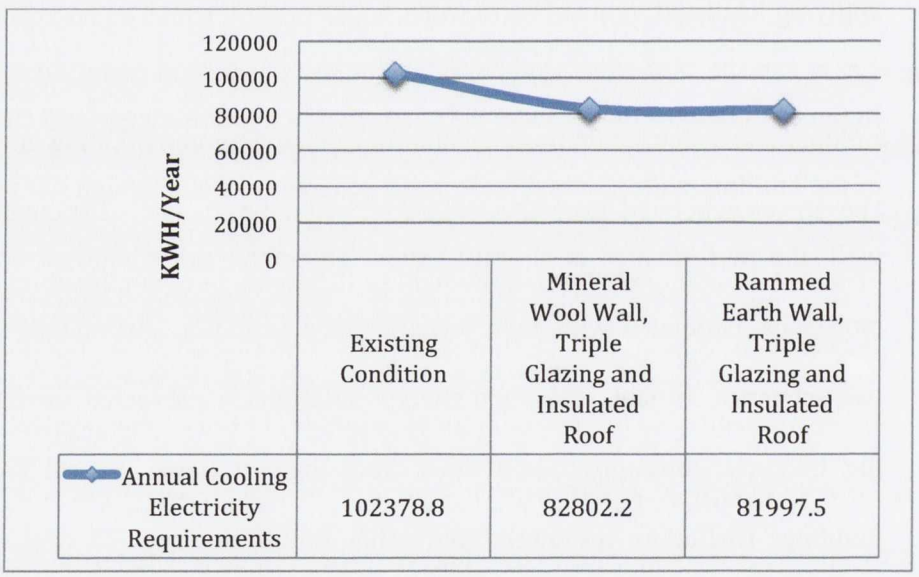
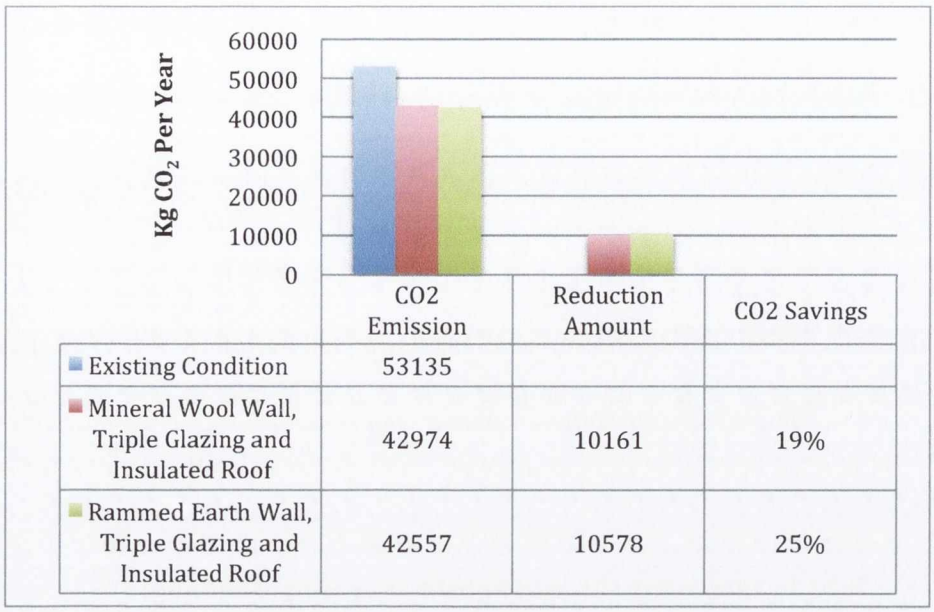


Figure 7 . 19: Annual cooling system demand for existing condition and improved scenarios



	CO2 Emission	Reduction Amount	CO2 Savings
Existing Condition	53135		
Mineral Wool Wall, Triple Glazing and Insulated Roof	42974	10161	19%
Rammed Earth Wall, Triple Glazing and Insulated Roof	42557	10578	25%

Figure 7 . 20: Carbon Emissions Reduction Based on the Cooling System Requirements

Installing 450 m^2 of photovoltaic panels (PVs) on the building's roof can lead to significant reductions in grid-energy used and carbon emissions. The PVs installation can cover the entire energy required for air conditioning the sustainably improved building and a significant proportion of the existing air conditioning energy requirement. The power generated from the PVs (83,257.9 kWh- Table 7.25) covers approximately 77% of the existing energy requirement of the cooling system, resulting in a much lower proportion of energy required from the grid. More remarkably, the power generated by the PVs can provide the total electricity required for the cooling system (70% of the total building energy requirement) when used with the proposed mineral wool wall, triple glazing and insulated roof. In addition, using rammed earth walls, triple glazing, and insulated roof along with the PVs provides the electricity required by the cooling system plus a surplus for other requirements such as lights and appliances.

As aforementioned, the PVs generating the power required for cooling the building would lead to zero carbon emissions for cooling which would dramatically drop the total building carbon emissions.

On view of the above, several facts that are important in the Saudi Arabian current legislation are considered for discussion below. These are as follows:

- Cooling systems require 70 % of total electricity demand of residential buildings in Saudi Arabia (Saudi Electricity Company, 2015).
- The current electricity tariff for residential buildings is 1.3 US cents per kw/h.
- The current government subsidy equals to 75% of the actual electricity bill.

7.17.1. Electricity Bill and Subsidy (Existing Building):

Although there is a high upfront cost associated to the PVs installation, the payback period (23 years) could be shortened by the assigning of electricity subsidy money to support and provide solar PVs at subsidized prices. This along with savings on yearly consumption could make it more reasonable and worthy of application. The total existing building electricity consumption is calculated below based on the simulation findings and the Saudi Electricity Company's findings.

Total Building Electricity Requirement = 102378.8 kWh/year (cooling demand) / 0.70 (70% of cooling system)

= **146,255.4 kWh/y**

Equation 7. 2: Total Building Electricity Requirement

The annual end-user electricity bill is calculated below based on the current tariff of 0.013 USD per kw/h for residential buildings.

Electricity Bill = 146,255.4 * .013

= **1901.3 USD/Year** including current 75% subsidy.

Equation 7. 3: Current Electricity Bill

Considering the fact that the government pays 75% of the bill, the annual government subsidy to the building can be calculated as presented below.

Total electricity bill for the building = 1901.3 * 4 = **7605.2 USD**

Then,

Total government subsidy to the building's electricity = 7605.2 – 1901.3

= **5704 USD/Year**

Equation 7. 4: Total Government Subsidy to the Building's Electricity

7.17.2. Electricity Bill and Subsidy (Rammed Earth, Triple Glazing and Insulated Roof):

Similarly, the total building electricity consumption (with the rammed earth scenario) is calculated below based on the simulation findings.

Total Building Electricity Requirement = 81997.5 kWh/year (cooling demand) / 0.70 (70% of cooling system)

= **117,139.2 kWh/y**

Equation 7. 5: Total Building Electricity Requirement (with Rammed Earth)

Considering the fact that the government pays 75% of the bill, the annual government subsidy to the building (with the rammed earth scenario) can be calculated as presented below.

Total electricity bill for the building = 1,522.8 * 4 = **6,091 USD**

Then,

Total government subsidy to the building's electricity = 6,091 – 1,522

= **4569 USD/Year**

Equation 7. 6: Total Government Subsidy to the Building's Electricity (with Rammed Earth)

However, considering that a large amount of the power is coming from the PVs (83257.9 kWh/y), the total power needed from the grid is calculated as shown below.

Total power needed from the grid = 117,139.2 – 83257.9 = **33,881.3 kWh/y**

Thus,

New electricity bill after PVs installation = 33,881.3 * .013

= **440.4 USD annually (with subsidy)**

Equation 7. 7: Total Power Needed From the Grid (with Rammed Earth)

As the government pays 75% of the bill, the annual government subsidy to the rammed earth building after PVs installation can be calculated as presented below.

Total electricity bill for the building after PVs installation = 440.4 * 4

= 1,761.8 USD

Then,

Total government subsidy after PVs installation = 1,761.8 – 440.4

= 1321.4 USD Annually

Equation 7. 8: Total Government Subsidy After PVs Installation (with Rammed Earth)

Therefore, the government can save on electricity subsidy per standard residential building when using rammed earth with PVs (4,383 USD per year). In addition, subsidy to existing building equals to 5,704 USD/Year and subsidy to the rammed earth and PVs building equals to 1,321.4 USD/Year.

Amongst the different scenarios modelled the rammed earth insulated walls, triple glazing windows, and insulated roof along with the monocrystalline photovoltaic panels on the roof evidenced the best performance with a significant environmental improvement with respect to the existing building and substantial economic savings.
The above calculations show that the government could save up to 76% of the funds currently spent subsidizing existing non-sustainable buildings. These funds could be invested on sustainable elements such as installing PVs.

According to the calculations above, the current electricity bill for the existing building is 1,901.3 USD per year with governmental subsidy while the bill would be 1,761.8 USD per year for the proposed enhanced building (with rammed earth and PVs) without governmental subsidy at all. This means that both the government and the end-user

benefit from the sustainable improvements as the government no longer needs to spend money on energy subsidies and the end-user pays less than the current subsidized price.

Comparing this scenario with the building's existing condition shows significant impact toward achieving the research aims and objectives. The results illustrate how much energy savings these enhancements provide in a sustainable manner. It shows that 72% of the building's electricity requirement is generated sustainably on site from the PVs installed on the building's roof. This amount, in fact, covers more than the required cooling system demand of the building. In addition, the proposed sustainable fabric (rammed earth) led to many savings in the energy required to cool the building as previously discussed. The U-values of the building fabric have improved to reach 0.29 W/m^2K with rammed earth walls instead of 0.72 W/m^2K for existing walls as an example. Other sustainable enhancements to the case study building like the insulated roof and the triple glazing also have been witnessed dramatical improvements as discussed earlier in this chapter.

Due to the energy savings and carbon emissions savings achievable using a combination of PV's and improved fabrics, it is strongly advised that these improvements are incorporated into building. Although there will be a higher upfront capital costs, the payback period will be quite short due to the annual energy savings. Amazingly, there will be a significant reduction in carbon emissions over the lifetime of the building with over a million kilograms of carbon emissions in a period of 20 years (based on a reduction of about 50,000 $kgCO_2$ per year).

In conclusion, sustainable elements simulated in this chapter have led to significant sustainable improvements when compared to the current building's condition. This increased the building performance in many ways providing about 72% of the energy required for the building onsite using solar PVs as a sustainable source of power. This

percentage can increase effectively by adding more sustainable elements. These elements include the use of energy efficient appliances and a passive building design and other technologies, which may eventually lead to more energy independence and further environmental savings.

Chapter Eight: Conclusion

Saudi Arabia has a great potential to apply sustainable principles in construction as it has the largest construction industry in the Middle East and in addition to the fact that stakeholders in construction are willing to become more sustainable.

The research proposed sustainable construction elements appropriate to Saudi Arabia. Initially, it studied the current status of sustainable construction through reviewing the literature and conducting questionnaire surveying and semi-structured interviews with key construction figures in the country. Three areas of focus were selected based on the importance given by the respondents and applicability into the Saudi construction industry. These three areas include the adoption of solar PVs, rammed earth walls and sustainable thermal insulation. Furthermore, a typical residential building in the city of Mecca was selected as a case study to apply the proposed sustainable elements using the Integrated Environmental Solutions (Virtual Environment) software which uses different tools including ModelIT, ApacheSIM, MacroFlo and SunCast.

Findings demonstrated that in the case study building with solar PVs with rammed earth walls and thermal insulation, 72% of the energy required is provided by the solar PVs. In addition, the total building carbon emissions lowered by 53789 $KgCO_2$ annually. In addition, the utilization of insulated rammed earth walls showed great energy savings when compared to the current non-insulated cement block walls; and insulation applied to roof also significantly reduced the building's total energy consumption.

Sustainable construction developments proposed and applied in this research can be achievable in Saudi Arabia only if sustainable regulations, legislation and green codes of practice are adopted. The awareness of the importance of sustainability among construction authorities is essential to promote this study outcome. In addition, green construction materials and market are key to enhancing sustainability in Saudi construction industry.

It was found that the PVs power had the greatest importance as 450 square meters of PVs installed on the roof of the case study building can provide the overall cooling energy requirement for the building with insulated rammed earth walls producing a power for other electricity requirements.

Research findings demonstrated that the proposed sustainable elements could save more than one million kilograms of carbon emissions during a building's lifetime of 20 years (based on the case study).

The findings suggest that the government subsidy towards electricity promotes non-sustainability in the construction sector: the total electricity bill of the case study building incorporating the proposed sustainable elements is lower than the current bill including government subsidy. Additionally, this would save approximately 7.3% of the current bill with no need for the governmental subsidy. This is a "both win" scenario as the end user would pay lower bills and the government would no longer spend money on subsidy.

This study has evidenced that the implementation of rammed earth construction; solar power generation with PVs and building insulation would significantly enhance sustainable construction in Saudi Arabia.

The research has also showed that substantial economic savings could be made by applying these sustainable elements. The application of these, in the case study building, would save approximately 70% of the money spent on electricity bills annually, not to mention the environmental impact minimization. In fact, a significant reduction in carbon emissions over the lifetime of the building could save over a million kilograms of carbon emissions in a period of 20 years (based on a reduction of about 50,000 $kgCO_2$ per year). In addition, the implementation of the sustainable elements investigated would

enable the government to stop subsidy and save these funds that could be invested into promoting and enabling sustainable construction. The proposed sustainable elements would also benefit end users, as they would consume less energy leading to lower energy bills without the need of the existing government subsidy.

The interviews and questionnaire revealed that many of people in the Saudi construction sector believe that sustainable principles would increase costs however they are not aware of the savings that these principles carry. Awareness is essential at this point, and it should be promoted among construction stakeholders across the country.

As evidenced in the questionnaire and interviews, most building professionals and authorities are aware of the negative environmental impact of construction therefore, the understanding is already in place. However, it was demonstrated that sustainable building regulations, information on economic savings and sustainable materials availability are needed.

The application of the outcomes of this research can improve current unsustainable practices in the Saudi Arabian construction industry. The background research and the interaction with the different construction stakeholders in the country suggest that a new stakeholder could be incorporated into the construction sector in Saudi Arabia. This could be a sustainability authority or organization to enhance sustainable construction and project management practices. According to the questionnaire and interviews analysis, the lack of standards and codes of practice managed by an authority responsible for sustainable activities is partially responsible for the unwillingness to develop construction in terms of sustainability. If such an authority was in place, the country development master plan could include stipulations and requirements to promote sustainable construction in future. This would lead to a sustainable society that cares about social heath, the economy and the environment. Over 80% of construction

professionals in Saudi Arabia included in this research are willing to apply elective green building standards. This should be given attention, as it is a strong base for moving forward toward achieving sustainability practices.

This research suggests that earthen materials should be considered in future plans and regulations. According to past practice, the performance and durability of earth materials has been proven in a hot, arid regions such as Saudi Arabia. Moreover, the modeling results of the insulated rammed earth walls in this research provided the best results among the different scenarios modeled.

The harsh desert climate of Saudi Arabia should be considered at design stage and later incorporated into the project life cycle as this would contribute to economic savings in the energy spent and would strongly lower environmental impact as well as providing a better indoor quality environment. For example, the local earthen materials, shadowing techniques and natural air ventilations (discussed in chapter 1) should be kept in mind during design and construction of new buildings as these principles would add value to enhance sustainability in construction. Solar irradiance in Saudi Arabia is unlike many places on earth. The abundance of daily sunlight in Saudi Arabia is the best way to achieve a renewable source of energy in buildings. Questionnaire and interview results urged the utilization of this source of energy in construction. Additionally, the results of the modeled PVs showed that Saudi Arabia could depend on solar power as the case study building can reduce the dependence on power from the grid by over 70%.

Construction management problems such as accelerated construction schedules should be avoided as this may end up with technical, social, economical and/or environmental problems as aforementioned in Chapter 2. However, the incorporation of new sustainable construction management methods is essential to enhance sustainable projects.

Life Cycle Assessments (LCA) of construction materials as well as the embodied energy of construction materials should be considered and/or regulated during the early stages of a project. This would measure potential impacts on the environment minimizing these impacts prior to construction. Coordination and cooperation to manage resources in a more efficient way is a primary need to be considered in future construction practices.
The International Green Construction Code (IgCC) could be applied in Saudi Arabia since there is no existing green construction code at the moment. However, a new Saudi Green Construction Code should be established based on local conditions and particular needs.

An adapted document could be drawn from the European Construction Design and Management regulations (CDM regulations) as a legal guidance for people working on construction site to enhance a health and safety in construction.

A "pilot sustainable construction regulation for Saudi Arabia" can be suggested based on the current sustainable construction literature review, research questionnaire and interviews and modeling. These can constitute a basis from which policy makers, professionals and government authorities could build up. The priority areas that this research evidenced are as follows:

1) Applying The International Green Construction Code (IgCC) as a basis to begin with - while working to build more specific standards and codes of practice.

2) Standardizing earth construction (rammed earth) for residential and low rise buildings (specifications such as those in New Zealand, Australia and other countries could be studied in detail and applied if suitable).

3) Specifying solar PVs for building roof's to minimize environmental and economic impacts on grid electricity (generated from fossil fuel). This could be

made mandatory for all new buildings and to any rebuild, renovation or retrofit.

4) Sustainable thermal insulation can be made mandatory for new buildings and to any rebuild, renovation or retrofit.

5) Shading systems should be applied in new buildings to reduce the direct sunlight/heat on the building fabric. Traditional Rawshans and Mashrabiyas can be readapted to new construction in some regions as a sustainable solution to openings.

6) A light color on the external building fabric should be specified to reflect sunlight and avoid heat transfer into the building fabric as seen in past construction in Chapter 1.

7) Construction waste materials generated on site must be segregated and stored before collection.

8) A certain percentage of recycled materials and sustainable construction materials should be used in any new building.

9) Other issues that would enhance sustainability may include the following:

    - Mixed mode ventilation systems (natural and mechanical ventilation systems) should be one of main components of new buildings as these reduce reliance on the mechanical (power consuming) ventilation systems currently used (Chapter 1). 10% of the total floor area could be the allowance for openable windows or doors in all new buildings as currently practiced in the hot regions like in Dubai, UAE. This provides cross natural ventilation, improves indoor air quality and cools down indoor temperature having great potential for energy saving. In fact, in

Saudi Arabia, at least part of the year open widows or doors allow the use of natural ventilation instead of mechanical ventilation.

- A minimum of 50% the area of the land (excluding building area) must be vegetated with local plants that consume low water in irrigation.

- Water conservation tools that reduce water consumption should be applied in new buildings as well as buildings to be renovated or rebuild.

- Wastewater generated by buildings should be preserved for use of irrigation.

Chapter Nine: Recommendations

Based on the conclusions, the following recommendations are proposed for future consideration to enhance sustainability in Saudi Arabian construction industry:

- Sustainable regulations and laws are key to enhancing sustainability. In Saudi Arabia, however, sustainable building laws and regulation are not in place. This research strongly suggests that these should be implemented and promoted in a practical manner.

- The application of further sustainable construction elements in Saudi Arabia need to be investigated such as new green materials, green roofs and other traditional methods and techniques.

- Not only residential but also commercial and industrial buildings need to become more sustainable. Further research is indeed in these types of buildings. For instance, the high-rise buildings may or may not use the same methods implemented in this research. They can use solar panels on walls instead of the roofs as this seems to be more effective to benefit the most. In addition, the use of solar panels on the roof of this type of buildings will generate a proportion amount of power but for sure will not share a high percentage of power requirements when compared to smaller types of buildings like residences. In fact, more studies and analyses with different sustainable approaches may show great advantage in one type of buildings and show less advantage or no logic in other types of buildings.

- The construction material market and crafts need to refocus onto enhancing sustainability. Major providers should introduce sustainable construction materials as well as a specialized workforce. A priority should be given to local materials.

- The research findings suggest that the government may no longer subsidize the electricity for the benefit of the government itself, electricity end-users, the

economy and the environment. It is evidenced in this research that the government has a great potential to stop subsidy by enforcing the application of sustainable principles across the country through laws and regulations.

- This research proposes that new legislation should be implemented in the followings areas:
    - Discontinuing energy subsidy
    - Tightening up building codes to encourage the use of sustainable materials and insulation
    - Tightening up tendering procedures and the use of pre-qualified contracting firms
    - Use of recycled materials

It has been determined in this research that Saudi Arabia is lagged behind the world in terms of sustainable application and practices. The research outcomes have contributed to the knowledge and tried to fill in the huge gap at least for some sustainable elements that are worthy of application and consideration in the near future. The contribution also includes providing sustainable solutions to current unsustainable industry that lack to innovation and sustainable guidance. However, the policy makers could be informed by presentation of this research outcomes to them through all possible means including TV programs, social networking and personal meetings. In fact, facts and figures from this research have the ability to be catalysts of change in a country were some social, economical and environmental issues are rising. The implementation of these could be done through the Saudi Standards, Metrology and Quality Organization (SASO), Ministries, private sector and all other stakeholders.

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Appendix A

Questionnaire Design and Form

Questionnaire About Sustainable Constructions in Saudi Arabia

Dear,

I am a PhD research student at Trinity College Dublin, Republic of Ireland. My research is about sustainability and green constructions in Saudi Arabia especially Mecca. The research aims to come up with a best green construction practices and regulations for the area of the research. The Saudi Arabian Ministry of Higher Education is the sponsor of the research.

However, your response is critical and central to the main results of the research. Your appreciated efforts toward completing this questionnaire are highly at value to us.

Please note that all responses are confidential and there is no way for identifying the identity of any of the respondents.

Sultan Alshareef

PhD Research Student

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Please, write one answer in the space provided just before each question excluding the first three questions, or write your own answers where textboxes are provided.

Part A: Personal and Work Experience:

1) **Name:** ..... **Age:**

2) **Work position:**

3) **Company/Organization's name:**

4) _____ **Years of experience?**

   A. Less than 5 years

   B. 5 to 10 years

   C. 11 to 15 years

   D. Over 15 years

Part B: General Green Construction Practices:

1) _____ **What type of green building regulations you practice currently?**

   A. Regional, specify _____

   B. International, specify _____

   C. None

2) _____ **Have you or your company/institution applied any green techniques or methods in any past projects?**

   A. Yes, specify _____

   B. No

3) _____ **Do you or your company/institution apply any green techniques or methods in current projects?**

A. Yes, specify _____

B. No

4) _____ **Will you or your company/institution apply any green construction techniques or methods in future projects?**

A. Yes, specify _____

B. No

5) _____ **How important is the green building regulations to the future of Saudi Arabian construction industry especially Mecca?**

A. Extremely important

B. Moderately important

C. Slightly important

D. Not important

6) _____ **Will you or your company/institution apply a new "Elective" green building regulations specified for Saudi Arabia?**

A. Yes to all green regulations

B. Yes to minimum green regulations

C. Depends on time and cost consequences

D. No, unless it is mandatory

7) _____ **Why green building applications yet not considered in Saudi Arabia?**

A. Lack of awareness

B. Lack of green infrastructures

C. High cost

D. Not useful

E. Other,_____

8) _____ **Why do you think Saudi Green Building Council is still inactive?**

A. Lack of support

B. Still in foundation stage

C. Lack of interested members

D. Low interest from decision makers

E. Other,_____

9) _____**Does the use of governmental incentives help in achieving more green constructions?**

A. Yes, specify _____

B. No

10)_____ **In your opinion, are the public aware of the advantages of sustainable constructions on the Environment and society?**

A. Yes

B. No

Part C: Construction and Project Management:

1) _____ **What level of green buildings experience a consultant/project manager should have in order to execute a new green construction?**

A. LEED accredited professional

B. Experienced

C. Not relevant

2) _____ **At project level, should green building assessment methods such as LEED regulated to all new buildings?**

A. Yes

B. No

3) **How to improve on-site green construction total work?**

4) **In a project bidding process, what considerations should be taken order to encourage sustainability?**

5) **What is the selection criterion in team selection phase in order to better mange a green construction?**

6) **_____ Should external stakeholders be involved in pre-project implementations to achieve more sustainability?**

A. Yes, specify _____

B. No

Part D: Materials:

1) **What construction materials you/your company mostly use? Why?**

2) **_____ Do you use any green building materials or products in any project involvement?**

   C. Yes, specify _____

   D. No

3) **_____ Despite the high initial cost of green constructions/materials, will you apply it to any project engagement? If Yes, Why?**

   A. Yes,_____

   B. No

4) **_____ Would you use any green techniques, methods, components or materials from the historical/ancient constructions of Saudi Arabia?**

   A. Yes, specify _____

   B. No

5) **_____ Will government subsidization of green products/materials help toward achieving sustainability goals in the near future?**

   A. Yes, specify _____

   B. No

   C. Other

Part E: Energy and Water:

1) _____**Should the government invalidate subsidization to energy in order to succeed in reducing energy consumption?**

   A. Yes, specify _____

   B. No

2) _____**What type of green energy sources should be used to support sustainable constructions in Saudi Arabia? How?**

3) _____**What mandatory regulations to use to enhance low-energy-consumption by building occupiers?**

4) _____**What energy source(s) you depend on in construction involvements?**

   A. Energy from fuel sources

   B. Energy from solar panels

   C. Mixed of both

5) **_____What types of water conservation tools you adopt in any construction involvement?**

Part F: Environment:

1) **_____What degrees of negative impacts that current Saudi buildings have on the surrounding environment?**

   A. High impact
   B. Medium impact
   C. Low impact
   D. No impact

2) **Do you implant local plant species in the planted area of constructions' site?**

   A. Yes, specify _____
   B. No
   C. Do not care

3) **Did you use vegetated roofs in any project constructions?**

   A. Yes, specify _____
   B. No

Appendix B

Semi-structured Interviews' Questions and Letter

Dear Interviewee,

I am a PhD research student at Trinity College Dublin, Republic of Ireland. My research is about sustainability and green constructions in Saudi Arabia especially Mecca. The research purpose is to come up with a best green construction practices and regulations for the area of the research. The Saudi Arabian Ministry of Higher Education is the sponsor of the research. In fact, the participations and statements that you provide are critical and important to the main research outcomes.

Please note that all responses are confidential and there is no way for identifying the identity of any of the respondents.

Sultan Alshareef

PhD Research Student

Trinity College Dublin

Dublin, Republic of Ireland

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Part One:

Name: .....

Organization's Name: .....

Position in the Organization: .....

Email Address: .....

How long have you been working in this organization? .....

Years

Describe your current roles and responsibilities?

.....