TECHNO-ECONOMIC ASSESSMENT OF ENERGY RETROFITTING TRENDS IN RESIDENTIAL BUILDINGS IN HOT HUMID CLIMATE

BY

WAHHAJ AHMED YAQUB

A Thesis Presented to the
DEANSHIP OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

In

ARCHITECTURAL ENGINEERING

DECEMBER, 2018

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS
DHAHRAN- 31261, SAUDI ARABIA
DEANSHIP OF GRADUATE STUDIES

This thesis, written by **WAHHAJ AHMED YAQUB** under the direction of his thesis advisor and approved by his thesis committee, has been presented and accepted by the Dean of Graduate Studies, in partial fulfilment of the requirements for the degree of **MASTER OF SCIENCE IN ARCHITECTURAL ENGINEERING.**

Dr. Baqer M. Al-Ramadan
Department Chairman

Dr. Muhammad Asif
(Advisor)

Dr. Salam A. Zummo
Dean of Graduate Studies

Dr. Adel Alshibani
(Member)

25/12/18

Date

Dr. Daeung Kim
(Member)

Dedicated to my beloved parents, family members and all loved ones

ACKNOWLEDGMENTS

I would firstly like to express gratitude and praise to the Almighty Allah for empowering me with the knowledge, strength and ability to complete this work and obtain my degree.

I would like to express my deepest gratitude and appreciation to my advisor Dr. Muhammad Asif for his inspiration, support, guidance and valuable time throughout the duration of my thesis. Appreciation is also due to the committee members Dr. Adel Alshibani and Dr. Daeung Kim for their valuable contribution to ensure the success and completion of my thesis.

I would also like to express my deepest of appreciation to the chairman of Architectural Engineering Department, Dr.Baqer Al-Ramadan, and all the faculty members for their continuous support and cooperation during my whole studying years. I also wish to thank the Deanship of Graduate Studies for allowing me the opportunity to pursue my higher education at KFUPM.

Finally, I would like to thank from the bottom of my heart my family members, especially my parents without whom I could not have grown to achieve this accomplishment.

TABLE OF CONTENTS

ACKNOWLEDGMENTS V

TABLE OF CONTENTS VI

LIST OF TABLES X

LIST OF FIGURES XI

LIST OF ABBREVIATIONS XIII

ABSTRACT XV

ملخص الرسالة XVI

CHAPTER 1 INTRODUCTION 1

1.1 Background 1

1.2 Statement of the Research Problem 8

1.3 Significance of the Research 9

1.4 Research Objectives 9

1.5 Scope and Limitations 10

1.6 Research Methodology 11

CHAPTER 2 LITERATURE REVIEW 14

2.1 Challenges of Sustainable Development in Saudi Arabia 14

2.2 Energy Retrofitting of Existing Residential Buildings-Global Trends in Existing Literature 18

2.2.1 Top-Down Studies Globally 19

2.2.2 Bottom-up Studies Globally 19

2.3 Existing Retrofit Studies in MENA Countries and Saudi Arabia 22

2.3.1 Top-Down Studies in Other MENA Countries 23

2.3.2 Bottom-Up Studies in Other MENA Countries 24

2.3.3 Top-Down Studies in Saudi Arabia 25

2.3.4 Bottom-Up Studies in Saudi Arabia 26

2.3.5 Summary and shortcomings in Existing Retrofit Studies in Saudi Arabia 27

2.4 Identification of Applicable Energy Efficiency Measures (EEMs) in Saudi Arabia 27

2.4.1 Increasing Cooling Set Point Temperature 29

2.4.2 Using Energy Efficient Housing Appliances 30

2.4.3 Replacing Conventional Lights with LED 31

2.4.4 Applying Window Shading 31

2.4.5 Improving Glazing Type 32

2.4.6 Improving Air Tightness 32

2.4.7 Using More Efficient HVAC System 33

2.4.8 Adding Envelope Insulation 33

2.5 Using Building Information Modelling (BIM) to Retrofit Existing Buildings 34

2.6 Policies, Barriers and Incentives of Energy Retrofitting 37

2.7 Economic Analysis Methods 38

CHAPTER 3 RESEARCH METHODOLOGY 40

3.1 BIM Based Framework for Energy Retrofitting of Existing Buildings 40

3.2 Case Studies 43

3.2.1 Case Study 1 - Villa 43

3.2.2 Case Study 2 - Apartment 48

3.3 Building Information Model (BIM) Development and Application 53

3.3.1 BIM Model Development 53

3.3.2 BIM Application in Retrofitting 56

3.3.3 BIM Interoperability with Building Energy Modelling (BEM) 58

3.4 Building Energy Modeling ... 60
3.4.1 Case Studies Model Calibration ... 63
3.5 Rooftop PV Electricity Generation ... 66
3.6 HVAC System Maintenance Practices Survey ... 66
3.7 Economic Analysis Method ... 68
3.8 Environmental Analysis Method ... 70
CHAPTER 4 ENERGY EFFICIENCY MEASURES (EEMS) ... 71
4.1 Increasing Cooling Set Point Temperature ... 74
4.2 Using Energy Efficient Housing Appliances ... 75
4.3 Replacing Conventional Lights with LED ... 76
4.4 Applying Window Shading ... 77
4.5 Improving Glazing Type ... 78
4.6 Improving Air Tightness ... 79
4.7 Using More Efficient HVAC System ... 80
4.8 Adding Envelope Insulation ... 82
CHAPTER 5 RESULTS AND DISCUSSIONS ... 84
5.1 HVAC System Maintenance Practices Survey Results ... 84
5.2 Energy Analysis ... 87
5.3 Retrofit Plan Levels ... 89
5.3.1 Initial Costs of Implementing each EEM ... 89
5.3.2 Categorization of EEMS into Levels ... 91
5.4 Economic Analysis ... 94
5.4.1 Annual Electricity Bills ... 94
5.4.2 Payback Period ... 96

5.4.3 Net Present Value (NPV) 97

5.5 Rooftop PV Energy 102

5.6 Environmental Analysis 103

5.7 Final Energy Retrofit Plans 104

CHAPTER 6 CONCLUSIONS AND FUTURE WORK 108

6.1 Conclusions 108

6.2 Future Work 110

REFERENCES 111

VITAE 120

LIST OF TABLES

Table 1: Summary of EEMs Used in Literature for Energy Consumption Reduction in Saudi Arabia. ... 28
Table 2: Villa Case Study Detail Description ... 45
Table 3: Apartment Case Study Detail Description ... 50
Table 4: Generated Electricity from Rooftop PV ... 66
Table 5: Electricity Tariff in Saudi Arabia ... 69
Table 6: Summary of the Proposed EEMs ... 73
Table 7: Existing and Proposed Envelope Details ... 83
Table 8: Summary of Energy Analysis Results and Retrofit Level Proposal ... 88
Table 9: Capital Costs for LED ... 89
Table 10: Capital Costs for Appliances ... 90
Table 11: Capital Costs for Window Shading ... 90
Table 12: Capital Costs for Double Glazing ... 90
Table 13: Capital Costs for Infiltration ... 90
Table 14: Capital Costs for HVAC System ... 91
Table 15: Capital Costs for Insulation ... 91
Table 16: Categorization of the EEMs into Retrofit Levels Based on Cost ... 92
Table 17: Electricity Cost for Existing and Retrofitted Cases - Villa ... 95
Table 18: Electricity Cost for Existing and Retrofitted Cases - Apartment Building ... 95
Table 19: SPP of each EEM ... 96
Table 20: CPP of each Retrofit Implementation Plan Level ... 97
Table 21: NPV of each Scenario and Savings Compared to Existing ... 101
Table 22: NPV Savings of each Scenario with Increased Electricity Tariff Rates ... 102
Table 23: Energy Offset by Rooftop PV Application in Existing Case and Retrofitted Cases ... 103
Table 24: CO2 Emission Reduction of Each Retrofit Level ... 104
Table 25: Energy Retrofit Plan Summary ... 105

LIST OF FIGURES

Figure 1: Observed Change in Average Surface Temperatures in Last Century. Source (Freedman, 2013).. 2
Figure 2: Global Consumption by Sector in 2011. Source: (IEA, 2013)........................... 2
Figure 3: Per Capita Energy Usage in Saudi Arabia & World.Source:(IEA, 2014)........... 4
Figure 4: Energy Usage by Sectors in Saudi Arabia. Source:(KAPSARC, 2016b) 4
Figure 5: Energy Efficiency Measures (EEMs) Pyramid. Source: (Holladay, 2010)......... 7
Figure 6: Methodology Flowchart. 13
Figure 7: Applicable EEMs in the toolkit and amount of energy consumption reduced by each EEM. Source: (Konstantinou & Knaack, 2011)....................................... 21
Figure 8: BIM-based Framework for Energy Retrofitting Proposed by Sanhudo et.al. ... 36
Figure 9: BIM Based Framework to Retrofit Existing Buildings.................................... 42
Figure 10: Top: Ground Floor Plan, Bottom: First Floor Plan 46
Figure 11: Top: East Elevation, Bottom: North Elevation 47
Figure 12: Top: Ground Floor Plan, Bottom: Typical Floor Plan 51
Figure 13: Top: East Elevation, Bottom: North Elevation 52
Figure 14: Image of the Villa BIM Model.. 54
Figure 15: Image of the Apartment Building BIM Model... 55
Figure 16: Example of BIM Use in Retrofitting Villa Case Study.................................. 57
Figure 17: Automatically Generated Villa Wall Schedule in Revit 57
Figure 18: Energy Analytical Model of the Villa 59
Figure 19: Energy Analytical Model of the Apartment Building..................................... 60
Figure 20: Energy Model of the Villa in DesignBuilder 62
Figure 21: Energy Model of the Apartment Building in DesignBuilder 62
Figure 22: Calibration of the Villa Case Study Energy Model.. 63
Figure 23: End-Use Energy Consumption of the Villa.. 64
Figure 24: Calibration of the Apartment Case Study Energy Model............................... 65
Figure 25: End-Use Energy Consumption of the Apartment Building............................ 65
Figure 26: Example of a Cash Flow Diagram for NPV.. 69
Figure 27: Energy Consumption Reduction-Cooling Temperature Set at 24◦C............... 74
Figure 28: Energy Consumption Reduction - Efficient Appliances 75
Figure 29: Energy Consumption Reduction - LED 76
Figure 30: Shading Device Design for the Villa.. 77
Figure 31: Energy Consumption Reduction – Window Shading Device 78
Figure 32: Energy Consumption Reduction - Double Glazing.. 79
Figure 33: Energy Consumption Reduction – Reducing Air Infiltration 80
Figure 34: Energy Consumption Reduction - Higher AC COP.. 81
Figure 35: Energy Consumption Reduction - Envelope Insulation.................................. 82
Figure 36: Web Diagram of Recommended Maintenance Schedule and Practiced Schedule in Saudi Homes... 86

Figure 37: Energy Consumption Reduction by EEMs in Villa 87
Figure 38: Energy Consumption Reduction by EEMs in Apartment Building 88
Figure 39: Energy Consumption Reduction by each Retrofit Plan Level in Villa 93
Figure 40: Consumption Reduction by each Retrofit Plan Level in Apartment Building 93
Figure 41: Cash Flow Diagrams of each Retrofit Plan Level of Villa.............................. 99
Figure 42: Cash Flow Diagrams of each Retrofit Plan Level of Apartment Building ... 100
Figure 43: Sensitivity Analysis for the Villa 101

LIST OF ABBREVIATIONS

AC/H	:	Air Change per Hour
ACCA	:	Air Conditioning Contractors of America
ANSI	:	American National Standards Institute
ASHRAE	:	American Society of Heating, Refrigerating and Air-Conditioning Engineers
AW	:	Annual Worth
BEM	:	Building Energy Modelling
BIM	:	Building Information Modelling
BIPV	:	Building Integrated Photovoltaic
B/C	:	Benefit/Cost
COP	:	Coefficient of Performance
DHW	:	Domestic Hot Water
DPB	:	Discounted Payback Period
EEMs	:	Energy Efficiency Measures
EU	:	European Union
EUI	:	Energy Use Index
GASTAT	:	General Authority of Statistics
gbXML	:	Green Building XML
GCC	:	Gulf Cooperation Council
HVAC	:	Heating Ventilation and Air Conditioning
IDP	:	Integrated Design Process

IEA	:	International Energy Agency
IECC	:	International Energy Conservation Code
IRR	:	Internal Rate of Return
KAPSARC	:	King Abdullah Petroleum Studies and Research Centre
KSA	:	Kingdom of Saudi Arabia
LCC	:	Life Cycle Cost
LCCA	:	Life Cycle Costing Analysis
LED	:	Light Emitting Diode
MENA	:	Middle East and North Africa
NPV	:	Net Present Value
O & M	:	Operation and Maintenance
PI	:	Profitability Index
PV	:	Photovoltaic
SASO	:	Saudi Arabian Standards Organization
SBC	:	Saudi Building Codes
SEC	:	Saudi Electricity Company
SEEC	:	Saudi Energy Efficiency Centre
SHGC	:	Solar Heat Gain Coefficient
SPP	:	Simple Payback Period

ABSTRACT

Full Name : Wahhaj Ahmed Yaqub
Thesis Title : Techno-Economic Assessment of Energy Retrofitting Trends in Residential Buildings in Hot Humid Climate
Major Field : Architectural Engineering
Date of Degree : December, 2018

One of the major contributors to climate change is the buildings and construction sector globally and within it more than 23% of the electricity was consumed in the residential sector in 2015. Energy consumption in Saudi Arabia is almost three times higher than the global average and one of the major contributors to that is the residential sector accounting for 52% of the total national consumption. Increasing environmental and economic concerns in the form of Saudi Vision 2030 mean that a sustainable residential sector in the future is inevitable and existing residential building stock in Saudi Arabia has to be retrofitted to reduce energy consumption. This study examines the energy retrofitting of existing homes in Eastern Province, Saudi Arabia. Applicable EEMs have been identified for the location and implemented. A BIM based retrofit framework has been proposed and implemented on the case studies and a three-level energy retrofit plan is proposed. Results indicate that annual energy consumption in a villa is reduced by 13.79%, 19.27% and 56.9% and in the apartment building by 22.84%, 28.85% and 58.5% for level 1, 2 and 3 retrofit respectively. CPP of implementing each retrofit level was calculated and in a villa investing in level 1, 2 and 3 retrofit will pay back in 0.23, 2.43 and 11.70 years respectively. For the apartment building, the payback period is 0.60, 11.28 and 24.60 years respectively. Overall in Eastern Region, implementation of the level 3 retrofit on existing unsustainable villas and apartment buildings will result in energy consumption reduction of 9,046.5 GWH annually transforming the residential sector into a more sustainable sector.

ملخص الرسالة

الاسم الكامل: وهاج أحمد يعقوب
عنوان الرسالة: تقييم تقني إقتصادي لاتجاهات تجديد طاقة المباني السكنية في أجواء المناخ الحار الرطب
التخصص: الهندسة المعمارية
تاريخ الدرجة العلمية: ديسمبر 2018

إن من بين العوامل الرئيسية التي ساهمت في تغير المناخ هو قطاع المباني والتشييد على مستوى العالم ، حيث إن 23٪ من الطاقة المستهلكة من هذا القطاع قد تمت إستهلاكها بالقطاع السكني في عام 2015، وإن استهلاك الطاقة في المملكة العربية السعودية أعلى بثلاثة أضعاف من المتوسط العالمي حيث إن من القطاعات المساهمة بشكل رئيسيي في ذلك هو القطاع السكني الذي يمثل 52 ٪ من إجمالي الاستهلاك الوطني للطاقة. إن تزايد المخاوف البيئية والاقتصادية في سياق رؤية 2030 السعودية تشير إلى أن وجود قطاع سكني مستدام في المستقبل أمر لا مفر منه وأن هنالك حاجة لإعادة تجديد المباني السكنية القائمة في المملكة العربية السعودية للتقليل من استهلاك الطاقة. تبحث هذه الدراسة في إعادة تجديد طاقة المنازل القائمة في المنطقة الشرقية بالمملكة العربية السعودية ، حيث تم تحديد حلول لكفاءة الطاقة (Energy Efficiency Measures) للموقع وتنفيذها ، وتم اقتراح وتنفيذ إطار عمل قائم على نمذجة معلومات المباني (Building Information Modeling) لإعادة تجديد طاقة مباني إستخدمت كدراسة حالة ، وتم اقتراح خطة إعادة تجديد الطاقة لهذه المباني في ثلاثة مستويات للحلول. تشير النتائج إلى أن استهلاك الطاقة السنوي في الفيلا يتم تقليله بنسبة 13.79٪ و 19.27٪ و 56.9٪ على التوالي لهذه المستويات ، وأما في مبنى الشقق فإن النتائج تشير إلى أن نسبة التوفير لهذه المستويات الثلاثة تكون 22.84٪ و 28.85٪ و 58.5٪ على التوالي أيضاً. تم تطبيق معادلة فترة إسترداد راس المال (Compound Payback Period) لحساب الفترة المستغرقة لإستعادة تكلفة الإستثمارات لكل من مستويات التجديد الثلاثة . تبين أن فترة إسترداد تكلفة الإستثمارات لهذه المستويات الثلاثة في الفيلا تكون 0.23 و 2.43 و 11.70 سنة على التوالي ، وبالنسبة لمبنى الشقق ، فإن فترة الاسترداد تكون 0.60 و 11.28 و 24.60 سنة على التوالي . بشكل عام سيؤدي تنفيذ التجديد الخاص بالمستوى الثالث على الفلل ومباني الشقق غير المستدامة الحالية إلى تقليل في إستهلاك الطاقة البالغ 9،046.5 جيجاواط ساعة سنوياً لتحويل القطاع السكني إلى قطاع أكثر استدامةً.

CHAPTER 1

INTRODUCTION

1.1 Background

Climate change is an inarguable fact and its evidence can be seen globally in the form of increasing natural disasters and global warming. Global warming is causing the temperature of earth to rise at an anomalous rate. Countries around the world are introducing measures to reduce the rate of global warming. One of the major contributors to climate change is the buildings and construction sector which is responsible for more than 40% of the materials consumption and more than one third greenhouse gas emissions globally (UNEP, 2009). In the past century some areas of the earth have experienced an increase in temperature by 2.5°C (Fig.1) (Freedman, 2013) and it is estimated that to limit global temperature rise by 2°C by 2050 would require a 77% reduction in total carbon dioxide emissions in the building sector compared to 2013 level (Thompson, 2014).Within the buildings and construction sector more than 25% of the global electricity was consumed in the residential sector in 2011 (Fig.2) according to the International Energy Agency (IEA, 2013) and thus it is absolutely necessary to invest in a sustainable residential sector in the future.

Saudi Arabia is a country with one of the world's most unsustainable residential sector and this is evident from the fact that the electricity usage in Saudi Arabia is much worse than the global scenario with per capita electricity usage being 9,140.35 kWh/person in 2014,

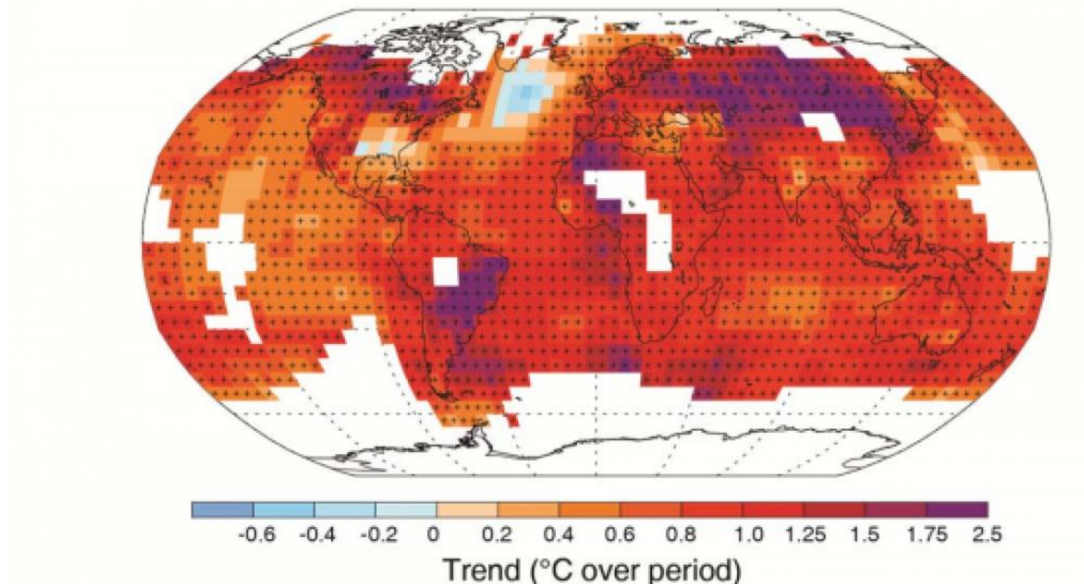


Figure 1: Observed Change in Average Surface Temperatures in Last Century. Source (Freedman, 2013)

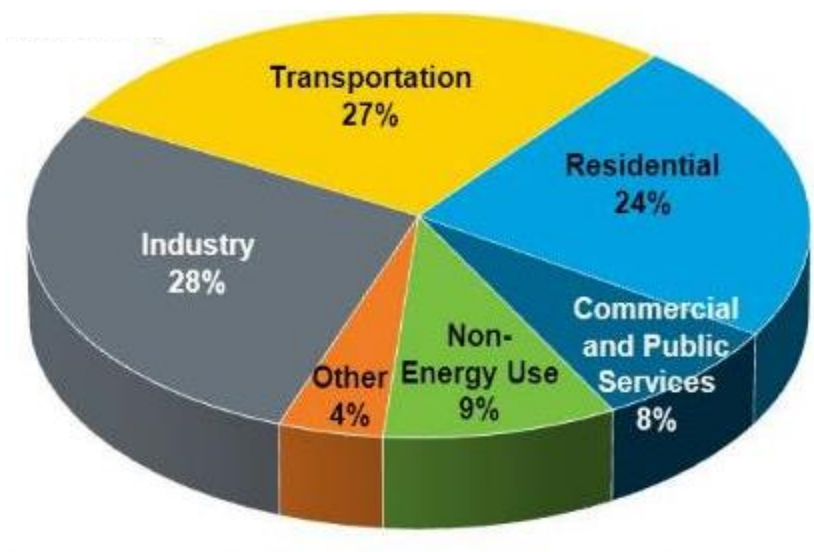


Figure 2: Global Consumption by Sector in 2011. Source: (IEA, 2013)

which is around three times higher than the world average (Fig.3) (IEA, 2014). The residential sector accounts for almost 52% (Fig.4) of the total national electricity consumption and this usage is expected to double by 2025 (Alyousef & Abu-Ebid, 2012). The sector has experienced a growth in electricity consumption of 85% from 2004 to 2014 growing from 73,365 GWh to 135,908 GWh (KAPSARC, 2016b). As a result, it is consuming the most amount of electricity as compared to all the other sectors in Saudi Arabia. One reason for such high percentage of increase in the residential electricity consumption is the high growth in the housing market. The growth is expected to continue for the country to meet the needs of the constantly growing population and around 2.32 million homes need to be built by 2020 (Sidawi, 2009). The housing market is ever-expanding due to high economic growth, favourable population demographics and increasing urbanization. Currently, apartments share the highest proportion of households in Saudi Arabia (41.1%), traditional house (26.2%), villa (17.7%) and floor of a villa (17.7%). (KCORP, 2013). In addition to growth, there are other challenges in the construction sector which result in the construction sector lagging behind in implementing energy efficiency strategies. For a sustainable future and to reduce the energy consumption and impact on environment of the residential sector, the expected homes to be built should be sustainable buildings and in addition to new sustainable homes, to render the residential sector sustainable it is absolutely necessary to reduce energy consumption of the existing building stock.

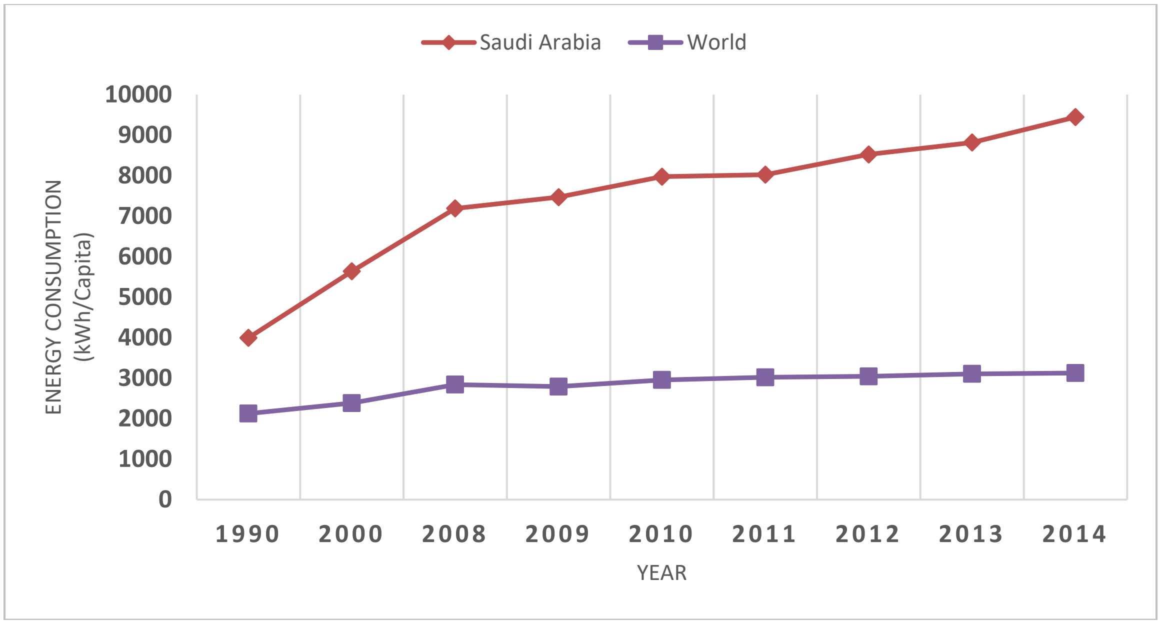


Figure 3: Per Capita Energy Usage in Saudi Arabia & World.Source:(IEA, 2014)

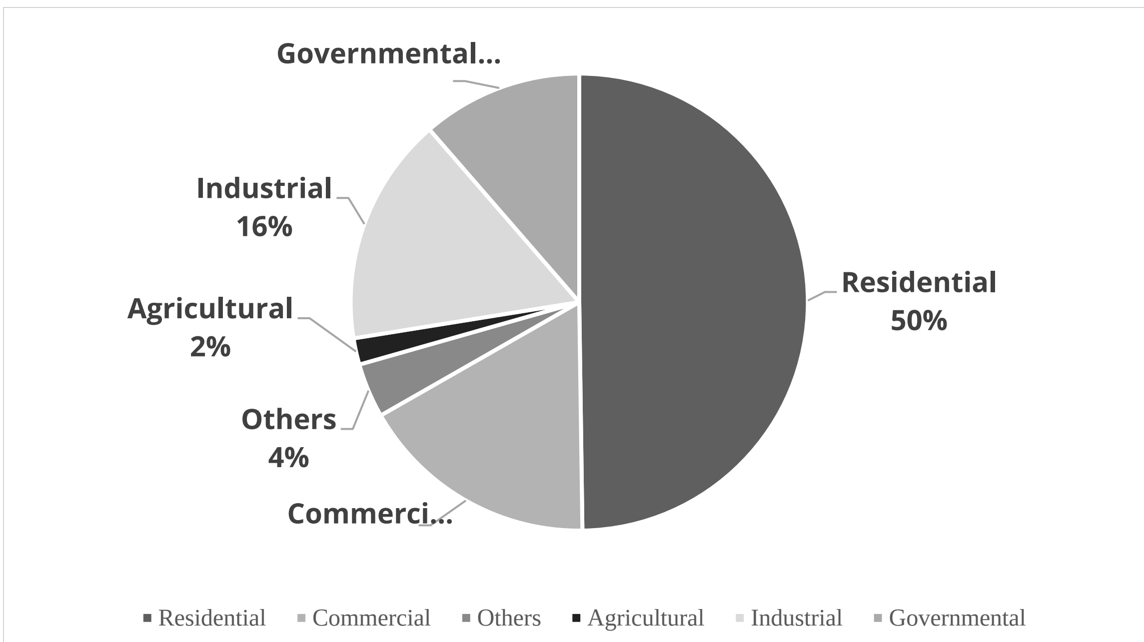


Figure 4: Energy Usage by Sectors in Saudi Arabia. Source:(KAPSARC, 2016b)

Existing residential buildings in Saudi Arabia are unsustainable as currently energy efficiency is overlooked by the residential sector stakeholders. Majority of the development do not take into account energy efficiency strategies in the buildings design and this is evident from the fact that 70% of the exiting residential buildings are not thermally insulated (SEEC, n.d.). Most of the development in Saudi Arabia only takes into account the capital costs and thus designed solutions and selected technologies are mostly the cheapest in cost and of low quality which are not environmentally friendly. O&M stages of buildings are not considered at all whereas studies dictates that majority of the energy consumption takes place during the operation of the building and 80% of total energy consumption occurs while operation of the building while less than 20% occur during the initial construction and preconstruction stages (Martinez, 2012). The reasons behind unsustainable development in Saudi Arabia are explained comprehensively in the following sections. Additionally, majority of the buildings to be present in future which will establish the built environment have already been built without taking energy efficiency into consideration. For example it is estimated that in UK that 75% of the buildings to be present in 2050 have already been built (Ravetz, 2008) (Wright, 2008). As a result, existing residential building stock is consuming high amounts of electricity and is unsustainable and should reduce the amount of energy consumption for a sustainable future. This can be done either by demolishing the existing buildings and building new sustainable homes or by the more feasible option of energy retrofit of existing homes to convert them to sustainable homes.

Energy retrofitting also known as energy refurbishment or energy renovation (DOE, n.d.) fundamentally means to upgrade a building’s components which directly or indirectly impact the energy consumption of the building. Direct components include lighting, heating, cooling etc. equipment that use energy as part of their function while indirect components include wall insulation, glazing type and other building envelope components which have an impact on the energy consumption of buildings by controlling environmental factors such as solar radiation allowed to pass through and air infiltration. These direct and indirect components are known as Energy Efficiency Measures (EEMs) (Fig. 5) and these can be classified into different levels (Holladay, 2010). These measures will be discussed in detail in the following sections. Energy retrofitting is generally classified into 3 levels; minor, major and deep energy retrofits ("Energy retrofits | Natural Resources Canada," 2017). The major difference between the 3 types of retrofit include the energy impact of the energy efficiency measures and the cost of them. Minor retrofitting involves low cost measures with minimum impact, major retrofit is more comprehensive and has higher impact that costs more than minor retrofitting and lastly deep retrofitting should be able to reduce energy consumption of buildings by over 50% according to experts (Scanlan, 2010). Furthermore, energy retrofit benefits are not limited to reducing energy consumption, environmental impact and saving costs in the long run but also attribute with it impact on the indoor environmental quality and the health and wellbeing of occupants (Paradis, 2016).

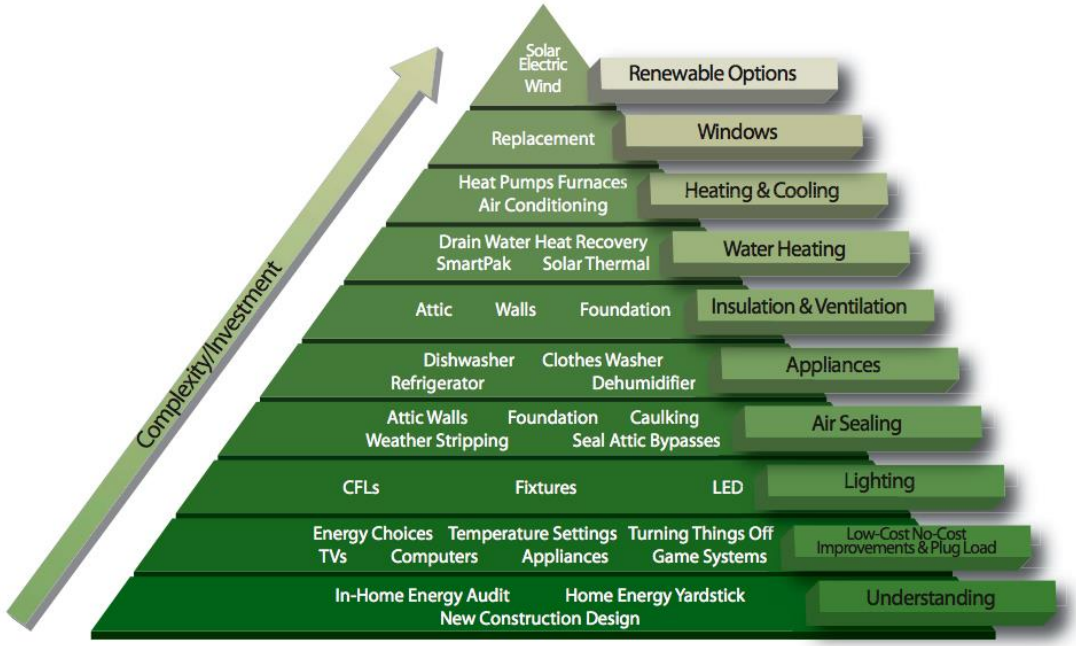


Figure 5: Energy Efficiency Measures (EEMs) Pyramid. Source: (Holladay, 2010)

An overview of global trends indicate that energy retrofit of existing building stock is one of the key priorities of developed countries. Energy retrofitting of the existing building stock is a major aspect of the EU directive which states that a 3% conversion of existing building stock by central governments is required to redevelop the entire stock by the year 2050 (BPIE, 2011). Therefore, European countries are developing policies and incentives for residential building sector stakeholders encouraging building owners to convert their buildings to sustainable buildings. Furthermore, in the United States energy retrofitting is currently at lower levels due to lack of interest, no available funding and insufficient incentives (Cassino et al., n.d.). In developing countries retrofitting of old buildings in general until now was being overshadowed by new energy efficient development as renovating old buildings is expensive (Thomsen et al., 2016).

Saudi Arabia is a developing country and energy retrofitting is at a very early stage and currently no prominent trend or action plan is present. The vision 2030 of Saudi Arabia considers sustainability its foremost priority and thus retrofitting of the existing unsustainable building stock should become a leading trend in the upcoming years. Studies are present discussing retrofit plans and strategies vaguely and a comprehensive study is required to assess the energy, environmental and economic saving potential in the residential sector utilizing the aid of latest technologies and tools.

1.2 Statement of the Research Problem

Residential sector in Saudi Arabia is consuming the most amount of energy, around 52% of the total national energy. The energy demand will continue to rise in the business as usual scenario. For a sustainable residential sector existing unsustainable homes should be retrofitted and then operated and maintained to achieve energy efficiency standards in the long run. However, energy retrofitting is a complex task and requires a detail study for successful implementation and adoption.

Majority of the current studies focus on the development of new sustainable homes and there is a lack of studies which focus on retrofitting the existing inefficient homes to sustainable homes. A clear retrofit plan is currently not present on the application of best energy efficiency measures that are applicable for homeowners as well as a plan taking into consideration homeowners' investment. A detailed energy retrofit study is required which fits the needs of individual housing topologies in Saudi Arabia taking into consideration building's existing condition, location, project specifications, retrofit strategies design and economic impact to the building owner. Currently there is no integration in the energy retrofit approach which present EEMs individually. Furthermore, new tools are now available which aid the process of retrofitting but are not yet investigated. There is a need for a study which takes into account latest computer applications and presents a holistic retrofit plan for residential buildings in Saudi Arabia which when applied results in significant energy savings and is cost effective.

1.3 Significance of the Research

While the residential sector in Saudi Arabia is consuming the most energy, it also presents the opportunity to reduce energy consumption by the most by introducing energy efficiency measures and policies. A comprehensive study examining the application and operation of appropriate energy efficiency measures for villas and apartments in hot humid climate is significant in shaping the industry and academics of Saudi Arabia towards developing the trend of energy retrofitting. Furthermore, this study will present a holistic and integrated approach to energy retrofitting of residential buildings in Saudi Arabia in terms of identifying energy efficiency measures and design and application of energy efficiency measures using latest design tools. Successful utilization and integration of Building Energy Modelling (BEM) and Building Information Modelling (BIM) in the re-designing process of selected case studies will guide and shift the existing construction industry from conventional methods to methods incorporating BEM and BIM to effectively retrofit the existing unsustainable residential sector of Saudi Arabia to become sustainable.

1.4 Research Objectives

The aim of the study is to assess the technological and economic aspects of energy retrofitting trends in the residential sector of Eastern Province, Saudi Arabia. The objectives include:-

1. Identify various applicable Energy Efficiency Measures (EEMs) for energy retrofitting of typical homes.
2. Assess the potential of Building Information Modeling (BIM) in energy retrofitting existing homes in Saudi Arabia
3. Perform energy analysis and measure the energy consumption reduction achievable.
4. Present an economically viable and practical energy retrofit plan suitable for application in existing homes.

1.5 Scope and Limitations

Studies with successful applications of energy efficiency measures which produce comprehensive and detailed retrofitting guidelines follow a three-step process requiring; 1) a detailed energy audit of buildings 2) energy retrofit design and 3) construction and monitoring of the measures on case studies for at least 1 year. This study will mainly focus on energy retrofit design due to the limitations of resources and time. Other limitations include:-

1. Limited to hot humid climate representing Eastern Region of Saudi Arabia.
2. Restricted to 2 typologies in residential buildings, villas and apartment buildings.
3. Limited BIM application as full-scale application of a BIM-based framework to retrofit existing buildings requires a range of expertise which can only be provided by a team of experts.

1.6 Research Methodology

The research approach is set to achieve the stated objectives in six main stages as outlined below and displayed in the methodology framework in figure 6.

Stage 1: Literature Review

- Conduct a detailed literature review of existing studies to identify the energy efficiency measures applied in retrofit projects globally and which are applicable in residential buildings in Saudi Arabia
- Identify the challenges in developing sustainable homes in Saudi Arabia and which led to the existing unsustainable development and identify the existing typical typologies of homes in Saudi Arabia.
- Study application and usage of BIM to retrofit existing buildings.

Stage 2: Data Collection

- Develop generic models for the 2 typologies (Villa and Apartment) in Saudi Arabia by conducting survey to identify current building characteristics including layout, construction details and other building systems.
- Survey existing homes to identify maintenance and operation regimes for HVAC equipment.

Stage 3: BIM Model

- Develop Building Information Modeling (BIM) Model: of the two existing typologies. Software to be used: Autodesk Revit.

- Study the scope of incorporating BIM in the retrofitting design and application process.

Stage 4: Energy Analysis

- Conduct Building Energy Modelling (BEM): Investigate the impact of the different Energy Efficiency Measures (EEMs) on the energy consumption of homes and analyzing the results to identify requirements for developing a sustainable home including EEMs and use of renewable energy techniques. Software to be used: Designbuilder.

Stage 5: Propose Initial Plan

- Develop a practical plan of implementation of energy retrofit by categorizing the EEMs and renewable energy techniques under 3 categories including Level 1, Level 2 and Level 3 retrofits. The framework will be based on the EEM's energy initial cost and energy consumption reduction.

Stage 6: Economic & Environmental Analysis

- Perform economic analysis: measure the investment required for each EEM and the life cycle cost (LCC) of the EEMs using the Net Present Value (NPV) method.
- Perform environmental analysis: Measure the amount of CO2 production reduced in each retrofit plan level.

Propose Final Plan.

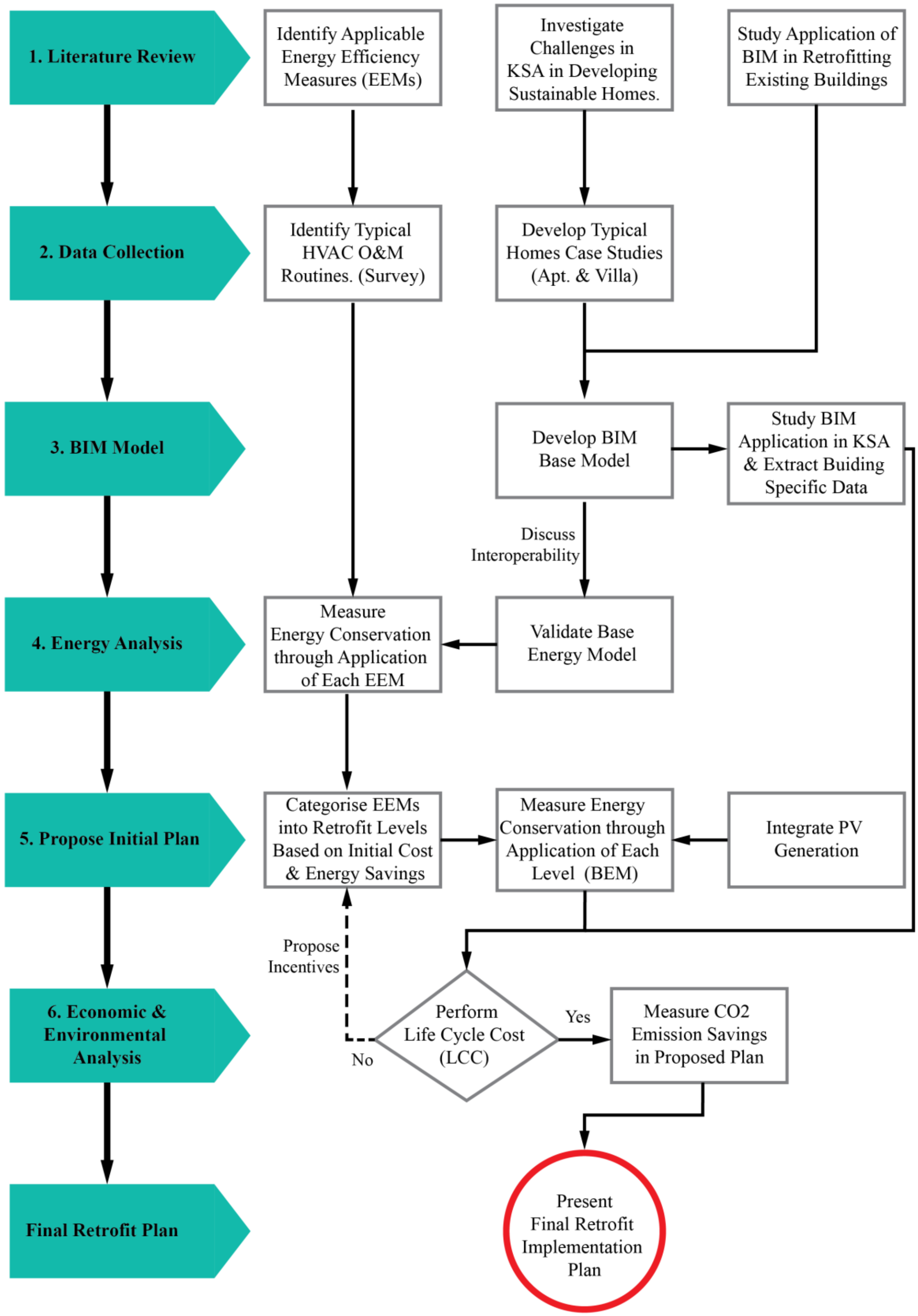


Figure 6: Methodology Flowchart.

CHAPTER 2

LITERATURE REVIEW

The literature review constitutes of studies which are relevant to understand and develop a deep understanding of the scope of energy retrofit of homes globally, in MENA region and in Saudi Arabia. Furthermore, the studies also cover the topics of:-

- Understanding the challenges in developing sustainable buildings in Saudi Arabia.
- Study and present shortcomings of existing retrofit studies.
- Identifying applicable EEMs globally, in MENA region and Saudi Arabia and their application on actual case studies.
- Application of building energy modelling and building information modeling tools to design and study the impact of EEMs.
- Economic impact of EEMs and how countries are developing policies which incentivize energy retrofit for homeowners.

2.1 Challenges of Sustainable Development in Saudi Arabia

Prior to developing energy retrofit plans, it is necessary to understand the existing challenges which have prevented sustainable development in Saudi Arabia. Development until now had to face unique challenges, some of which are natural and some man-made. Most of the development in the residential sector was and is unsustainable as designing and building sustainable residential buildings faces challenges largely present due to the climate of the country, subsidized utilities, outdated construction sector, rapid growth and inefficient policies.

Saudi Arabia has a very harsh climate and is characterized by hot and dry weather year round in most of the country resulting in buildings being exposed to large amounts of solar radiation for long periods of time (Sahin & Rehman, 2012). To offset the effect of solar radiation and cool down the indoor temperature for thermal comfort, buildings are severely are depending on air conditioning which consumes about 80% of household electricity in Saudi Arabia (SEEC, n.d.) (Akbari, Morsy, & Al-Baharna, 1996). Due to the harsh weather passive ventilation techniques are not applicable in most of Saudi Arabia and therefore it is a challenge to provide occupants with maximum thermal comfort while minimizing energy used in air conditioning.

Low electricity tariffs have resulted in unsustainable development over the years in Saudi Arabia. As a result of the subsidized cost, not much is invested in energy efficient solutions and users also consume electricity without paying much attention to minimizing electricity consumption resulting in homes consuming high amounts of energy. The low electricity tariffs result in lack of awareness from the end users and no energy efficiency initiatives are considered by homeowners in terms of building design such as not using thermal insulation in walls to save on capital cost and while selecting electrical equipment such as HVAC system and refrigerators (SEEC, n.d.). The resulting energy consumption in Saudi homes is higher than global average. In the eastern province, apartments consume around 196.5 kWh/m²/year, while traditional houses and villas consume 156.5 kWh/m²/year and 150 kWh/m²/year respectively (Alrashed & Asif, 2014). However, with the subsidy on the tariff being reduced awareness of sustainability in the general public is increasing and a survey study by Mohammed S. Al Surf and Lobna A. Mostafa (Al Surf & Mostaafa, 2017) showed that 92% of their respondents are aware of sustainability. This is a good sign and shows a step forward in the right direction for sustainable development.

However, the construction industry in Saudi Arabia is still depending on unsustainable practices. Alrashed, F., & Asif, M. found in their survey study that the construction industry in Saudi Arabia regards sustainability as one of its least important priorities (Alrashed & Asif, 2012) and a proof of this negligence is that around 70% of the buildings in Saudi Arabia are not thermally insulated (Mujeebu & Al Shamrani, 2016). Furthermore, a life cycle assessment of a Saudi Home found that over 91% of the material used for construction is concrete which is responsible for around 43.4% of the embodied energy of the house and impacting the environment the most (Asif et al., 2017). This has to change and the construction industry has to prioritize sustainability as the most important factor in designing and sustainable solutions and materials should be incorporated in the design of residential buildings.

As stated earlier, Saudi Arabia is a country with tremendous growth due to factors such as growing population, economic growth and modernization (Asif, 2016).The housing, commercial sector grew by an astonishing 850% in terms of floor area since the turn of the century (KAPSARC, 2016a). The high growth of the sector coupled with rapid construction which overlooks energy efficiency and only focuses on initial investment has cultivated a construction sector that is lagging in terms of implementing sustainable solutions leading to several factors which attribute to wastage of energy. These factors include deficient insulation, leaking windows, deficient heating and cooling systems and poor construction techniques.

Furthermore, policy incentives currently don't exist for owners/property developers for developing sustainable buildings. Policy incentives can motivate developers into investing in sustainable technologies such as renewable energy. Unfortunately, lack of incentives results in a challenging situation for developing sustainable buildings and currently is a barrier to sustainable development (AlRashed & Asif, 2012). Countries pursuing sustainable development have some sort of policies and measure in place which encourages the development of sustainable buildings. Unfortunately Saudi Arabia is lagging behind in introducing incentive measures and until recently there were no measures in place. Recently, the government has allowed net-metering which will result in encouraging the use of on-site renewable energy production however other incentives should also be implemented which encourage the construction of zero energy homes or near zero energy homes. Together with policy incentives, stricter building energy codes should be enforced. Currently there are building energy codes present in Saudi Arabia which are not enforced. Another initiative towards sustainable practices include the enforcing of using proper insulation in buildings by Saudi Arabian Standards Organization (SASO) which is also supported by Saudi Electricity Company (SEC) by not providing electricity to buildings with proper insulation, however developers and contractors find their way around this policy in order to save initial costs.

Regardless of these challenges, research shows that residents are willing to incorporate sustainable features in their dwellings and features such as solar PV system are the most attractive to users (Alrashed & Asif, 2015a). The residential sector in Saudi Arabia has the potential to produce 30% of the total electricity demand (Khan, Asif, & Stach, 2017). For a sustainable residential sector including development of new buildings and retrofit of existing buildings, these challenges need to be overcome. Particularly retrofitting existing buildings will not occur unless a thorough model is adopted from the top to down. The next section includes studies with successful applications of energy retrofitting in homes

2.2 Energy Retrofitting of Existing Residential Buildings-Global Trends in Existing Literature

Studies show that globally countries are investing and developing successful retrofitting projects to meet energy efficiency targets discussed in the preceding sections. Countries have identified that the potential for saving energy be energy retrofitting is substantial. A report by (Benningfield, 2009) indicates that in the US apartment buildings, if refurbished for energy efficiency, have the possibility to save over 51,000 GWh by 2020 thus resulting in yearly savings of up to $8 billion for tenants and property owners. Furthermore, a study by (Schlomann et al., 2009) found that in Europe a 78% reduction in the residential energy consumption is possible by 2030 as compared to 2004 level. As a result, numerous studies are present in literature for US and EU member states which investigate the energy savings in homes.

Energy retrofit studies present currently can be categorized into 2 categories; Top-Down and Bottom-Up studies. Top-down studies represent the whole building stock of an area by developing a prototypical model which is modelled for the whole building stock while Bottom-up studies are more focused and describe retrofitting for a specific case. Bottom-up studies usually look at case studies with more details going into the technical details of application of the EEMS and then the monitoring and O&M of each EEM if constructed.

2.2.1 Top-Down Studies Globally

(Terés-Zubiaga, Campos-Celador, González-Pino, & Escudero-Revilla, 2015) investigated the potential energy savings for social housing in Spain by implementing different EEMs including improved envelope insulation and improved glazing system. Their results indicated that it is possible for the existing building to conform to new energy regulations in Spain through the application of the proposed EEMs.

2.2.2 Bottom-up Studies Globally

(Taylor, Searcy, & Jones, 2016) identified that very few apartment building energy retrofit studies are existing for hot humid climate and studied the impact of energy efficiency retrofitting on an apartment building in Orlando, US. They studied 4 apartment buildings built during 1984 and 1995 and their EEMs included better efficiency heat pump, energy star refrigerator, solar window film, attic insulation, duct repair, water saving fixtures and efficient lighting fixtures. Their results indicate that annual savings of up to 29% is possible after the application of these measures.

(Ben & Steemers, 2014) selected a heritage apartment complex in London as an energy retrofit case study and simulated using IES software. Their EEMs included as cavity wall insulation, roof insulation, secondary glazing, air tightness, boiler upgrade and insulation hot water containers as well as the impact of improving occupant behavior. They discovered that positive behavior from tenant can impact the potential savings by up to 86%.

(Konstantinou & Knaack, 2011) carried a design-based approach towards energy retrofitting claiming that energy retrofitting is a design issue that is different for all cases. They developed a toolbox containing organized energy efficiency measures and their impact on the energy consumption. They applied their toolkit on a 3 story and 4 story apartment building in Germany and found that 92% and 80% less energy was required for heating in the 2 apartment buildings respectively (Fig.7).

(Kuusk & Kalamees, 2015) discussed the energy retrofit measures for an apartment building made out of bricks in Estonia (cold climate). The study analysed the energy usage of brick apartment buildings and 4 reference buildings were selected and simulated which represent the whole building stock of Estonia. They found that insulating walls had the highest effect on the reducing building energy consumption. Improving building envelope insulation, adding more efficient windows and a ventilation system with heat recovery will reduce energy consumption to match with the energy efficiency requirements of new apartment buildings.

(Thomsen et al., 2016) chose Traneparken apartment complex as a Danish case study for their study. The complex was retrofitted with EEMs including new facades, new windows, additional insulation, mechanical ventilation with heat recovery and a photovoltaic installation on the roof. They reduced the overall energy demand and energy bill for heating by 31%. The electricity demand for ventilation had gone up, but the electricity production from the PV system covered around 60% of this increase.

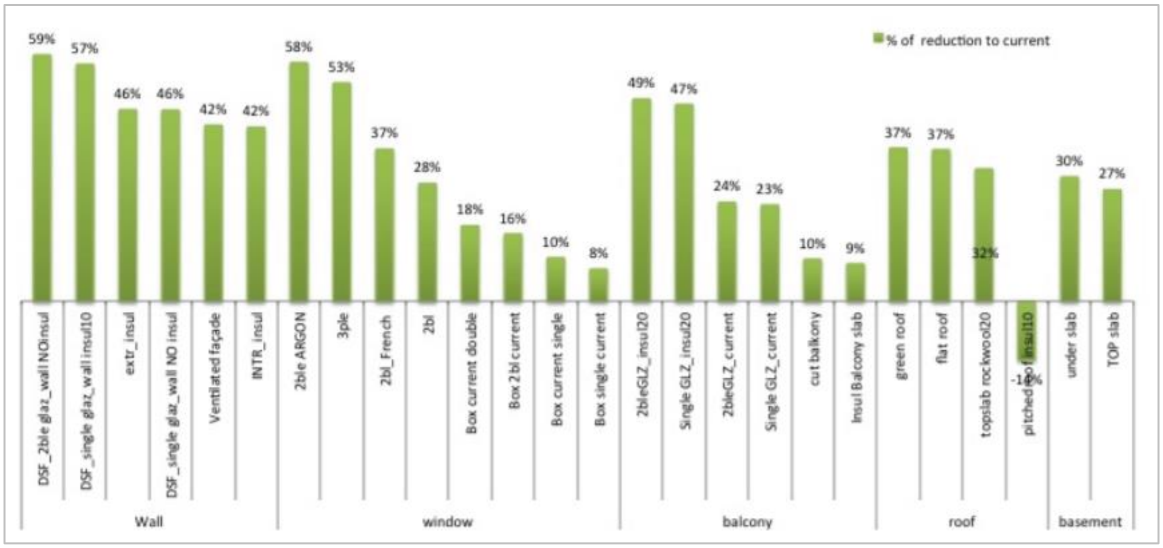


Figure 7: Applicable EEMs in the toolkit and amount of energy consumption reduced by each EEM. Source: (Konstantinou & Knaack, 2011)

(Evola & Margani, 2016) studied the viability of using building integrated photovoltaics (BIPV) on facades to retrofit an apartment building in Italy. In addition to BIPV, their proposed EEMs also included increasing thermal insulation of the buildings walls and improving the energy efficiency of heating and cooling systems. They found that the cost for BIPV can be returned in 9 years considering existing incentives and 50% self-consumption rate. The study highlighted the importance of incentives as they indicated that without incentives the BIPV would take 15 years to bring return to the investment.

(Synnefa et al., 2017) energy retrofitted a community apartment building of 7 floors in Athens, Greece. They conducted the energy retrofit by following a complete retrofit process which included improving envelope insulation, more efficient glazing, using ceiling fans, passive ventilation, smart coating on insulation, exterior shading, photovoltaic panels, LED lighting and a more efficient lighting system as the EEMs. Simulation was performed using TRNSYS software and EEMs were applied on to the actual building resulting in energy savings of 81% annually.

(Jones, Li, Perisoglou, & Patterson, 2017) energy retrofitted 5 houses in South Wales using envelope insulation, efficient boilers, minimizing air leakage, energy efficient lighting and appliances and use of Solar PV. They determined the applicable EEM from the above listed by conducting a survey for each house. After that, the EEMs were simulated using VirVil Sketchup and then applied to the houses. The results indicate that carbon dioxide emissions of up to 75% are possible and cast savings of up to 621 pounds per year.

(Miller, Liu, Amin, & Gray, 2018) examined the feasibility of converting an existing house to a net zero energy house in Australia. They conducted energy simulations using BersPro 4.1 software on various EEMs including adding roof insulation, window curtains for shading, photovoltaics, efficient heater, introducing natural light, efficient lights, better extractions fans, efficient ceiling fans and improved stove and constructed these EEMs on the house. They were able to achieve a 50% improvement in building thermal efficiency and generate 19.6 kWh from the photovoltaics.

(Hens, 2010) retrofitted an end of the row house in England for energy efficiency by insulating the envelope, using efficient glazing, implementing a ventilation system, efficient heating system and using a solar boiler. The EEMs were implemented on the house and the results measured over a period of time. Results indicate the energy use is reduced by about 20% annually.

2.3 Existing Retrofit Studies in MENA Countries and Saudi Arabia

Similar to the global studies, retrofit of residential building studies in the MENA region and in Saudi Arabia are also investigated.

2.3.1 Top-Down Studies in Other MENA Countries

(Krarti & Ihm, 2016) studied the potential of developing net-zero residential buildings in the whole MENA region. They developed a prototypical model representing the whole region and studied design features including orientation, window location and size, glazing type, wall and roof insulation levels, lighitng fixtures, appliances and efficiencies of heating and cooling systems. They found that a reduction in energy use by 50% is possible if current design practices are changed. Their study also indicated through economic analysis that for cost effective implementation subsidies have to be removed.

(Dubey & Krarti, 2017) studied energy retrofit investment options for the residential building stock of Bahrain. The developed a prototypical villa representing the entire building stock of Bahrain. Their study identifies the EEMs applicable in Bahrain as implementing low cost energy efficiency measures, installation of thermostat, replace existing lights with LED, Seal air leakage sources, Replace existing AC with higher efficiency system, Use energy efficient appliances, Use double glazing, Using shading device and Applying insulation. The study conducted a parametric analysis to assess the most effective single energy efficiency measures that can significantly reduce annual energy consumption and peak demand and then did an optimization analysis to categories these EEMs into the best combination which categorizes the EEMs into 3 categories based on the impact on investment required and the impact on energy consumption. They found that in the residential sector a level 1 energy retrofit investment of $545 million could reduce electricity consumption by 496 GWh/year, a level 2 investment of $3,236 million will reduce it by 1,422 GWh/year and a level 3 investment of $6,472 million by 3,091 GWh/year.

(Krarti, 2015) evaluated building energy efficiency retrofit program for Kuwait. The Kuwait building code of 2010 was compared to the original version established in 1983. A residential building was selected in Kuwait with prototypical characteristics and simulated using energy plus. Improved measures include envelope insulation, window type, size and shading, lighting efficiency, ventilation rate, and heating and cooling equipment efficiency. Results show that a savings of 32% is possible with the implementation of EEMs.

(Al-Ragom, 2003) also studied retrofitting residential buildings in Kuwait using a prototypical villa model which can represent around 70% of the housing typologies of Kuwait. The model was simulated and EEMs considered include envelope insulation, glazing type and window size. It was found that air conditioning load of up to 60% is possible in the prototypical home.

2.3.2 Bottom-Up Studies in Other MENA Countries

(AlFaris, Juaidi, & Manzano, 2016) studied energy saving potential for hot regions. They conducted a retrofit case studies for a villas in Dubai They have listed six techniques applicable to the housing sector in arid climate. These include Improvement of building's envelope, using efficient glazing shading coefficient, using roof coating, improving air tightness, controlling HVAC system according to demand and replacing conventional lights with LED lights. After applying these measures, up to 47.6% energy was measured to have been saved.

(Alexander Friess, Rakhshan, A.Hendawi, & Tajerzadeh, 2012) studied energy efficiency possible through the use of proper wall insulation. The selected a villa which can represent around 1000 houses in Dubai. Results suggest that around 30% energy reduction is achievable.

2.3.3 Top-Down Studies in Saudi Arabia

(Alaidroos & Krarti, 2015) in their study titled "optimal design of residential building envelope systems in the Kingdom of Saudi Arabia" analysed measures to improve the envelope systems in the residential sector of Saudi Arabia which can reduce the energy consumption. The EEMs studied include envelope insulation, window area, glazing type, window shading and thermal mass. Their analysis included modelling a prototypical model of a villa in the 5 climatic zones of Saudi Arabia using Energy Plus. They found that energy consumption can be reduced by up to 39.5%, 33.7%, 35%, 32.7% and 22.7% for Riyadh, Jeddah, Dhahran, Tabuk and Abha respectively. They concluded that without increasing the tariffs for residential sector, the government can save up to 36% on subsidies if they invest in retrofitting measures by covering initial cost of EEMs.

(Saleh, 1990) studied the impact on energy consumption when thermal insulation is implemented on a house in hot dry climates. A prototypical 1 floor villa was selected in Riyadh city and modelled with 10 different envelope systems. It was found that energy consumption can be reduced by up to 40%.

(Dubey, Howarth, & Krarti, 2016) have studied energy retrofitting in the residential sector of Saudi Arabia using a detailed top-down approach. They used a prototypical model of a villa to represent the housing stock of Saudi Arabia. Their study identifies the EEMs applicable in Saudi Arabia as implementing low cost energy efficiency measures, installation of thermostat, replace existing lights with LED, Seal air leakage sources, Replace existing AC with higher efficiency system, Use energy efficient appliances, Use double glazing, Using shading device and Applying insulation. The study conducted a parametric analysis to assess the most effective single energy efficiency measures that can significantly reduce annual energy consumption and peak demand and then did an optimization analysis to categories these EEMs into the best combination which categorizes the EEMs into 3 categories based on the impact on investment required and the impact on energy consumption. They found that in the residential sector a level 1 energy retrofit investment of $10 Billion could reduce electricity consumption by 16,000 GWh/year, a level 2 investment of $104 Billion will reduce it by 46,000 GWh/year and a level 3 investment of $207 Billion by 100,000 GWh/year.

(Ghabra, Rodrigues, & Oldfield, 2017) investigated the impact of architectural parameters on energy consumption of a prototypical apartment building in Jeddah. EEMs investigated include wall insulation, glazing type and window-wall ratio. Their findings indicate that cooling loads can be reduced by up to 77 by implementing these measure.

(Alajlana, Smiaia, & Elania, U, 1998) found that electrical energy consumption could be reduced by up about 50% annually if thermal insulation and other supporting tools are used in Saudi Arabia buildings.

2.3.4 Bottom-Up Studies in Saudi Arabia

(Al-Mofeez, 2007) studied a villa in Eastern Region of Saudi Arabia for improving energy efficiency. EEMs investigated include adding insulation to walls, air tightness was improved and ventilation rate was improved. Results indicate significant energy savings were achieved, 40%, in air conditioning energy consumption due to improving building envelope and the peak monthly load was reduced by 34% after the retrofitting.

(Taleb & Sharples, 2011) studied existing water and energy conservation strategies of current apartment buildings located in Jeddah, Saudi Arabia. They developed guidelines suggesting that several energy efficiency measures could have been incorporated in the design of the building if the building was still in its design The include improving envelope insulation, using higher efficient lights, using double-glazed windows, fitting shading devices and using thermal mass. If these solutions were implemented, the household could have reduced annual household electricity consumption by 32.4%.

2.3.5 Summary and shortcomings in Existing Retrofit Studies in Saudi Arabia

Global and MENA region studies have indicated clearly that individual energy retrofit projects have the potential to reduce energy conservation significantly. Investment options and economic impacts have also been studied and results indicated that subsidies should be reduced on electricity tariffs and incentives should be applied for EEMs. Furthermore, a lack of comprehensive retrofit study is seen in the Saudi Arabia as most studies are focusing on large scale retrofit plans' impacts and not on the technical and detailed aspects of energy retrofitting. Researchers have implemented various EEMs to achieve their targets. However, some of the retrofit strategies and techniques are not applicable in Saudi Arabia taking into account the climate and local context hence a list of EEMs need to be developed taking into account climatic conditions, economic impact and market availability of product. Also, studies utilizing latest design and application tools such as BIM are not currently present. A total of 9 studies are present for Saudi Arabia and none of them have a title including retrofitting" in them and thus majority of the lack a holistic approach to energy retrofitting.

2.4 Identification of Applicable Energy Efficiency Measures (EEMs) in Saudi Arabia

A number of EEMs have been used in the preceding studies globally and in MENA region. The EEMs used in the studies in Saudi Arabia in literature review are summarized in table

1. Implementing these EEMs can result in significant energy savings in residential buildings.

Table 1: Summary of EEMs Used in Literature for Energy Consumption Reduction in Saudi Arabia.

Study Ref.	EEMs	PV
(Alaidroos & Krarti, 2015)	Envelope insulation, window area, glazing type, window shading and thermal mass	No
(Dubey et al., 2016)	As implementing low cost energy efficiency measures, installation of thermostat, replace existing lights with LED, Seal air leakage sources, Replace existing AC with higher efficiency system, Use energy efficient appliances, Use double glazing, Using shading device and Applying insulation	No
(Ghabra et al., 2017)	Wall insulation, glazing type and w-w ratio	No
(Alajlana et al., 1998)	Thermal insulation	No
(Al-Mofeez, 2007)	Adding insulation to walls, air tightness was improved and ventilation rate was improved	No
(Taleb & Sharples, 2011)	Improving envelope insulation, using more efficient lights, using double-glazed windows, fitting shading devices and using thermal mass	No
(Abd-ur-Rehman, Al-Sulaiman, Mehmood, Shakir, & Umer, 2018)	Improving envelope insulation, using more efficient lights, using double-glazed windows, Using more efficient equipment	Yes
(Algarni, 2018)	Cool Roof	No
(Aldossary, Rezgui, & Kwan, 2014)	Window shading, double glazing	Yes
(Mahmoud, Asif, Hassanain, Babsail, & Sanni-Anibire, 2017)	Green Roof	No

However, not all of these can be implemented at once and practicality of implementing these solutions should be addressed as well from the individual owners' point of view. Furthermore, on site energy generation is also investigated by researchers and incorporating it in retrofit plans can lead to improved retrofit scenarios. From the above studies eight EEMs can be identified as the potential ones to be effectively and practically applied in Saudi Arabia residential buildings. These can be listed as:-

1. Increasing cooling set point temperature
2. Using energy efficient housing appliances
3. Replacing conventional lights with LED
4. Applying window shading
5. Improving glazing type
6. Improving air tightness
7. Using more efficient HVAC system
8. Adding envelope insulation

This following sections briefly describes each of the previously identified EEM applicable for retrofit projects in Saudi Arabia. The description includes general effects each EEM is predicted to have on the case studies based on previous studies and the science behind it.

2.4.1 Increasing Cooling Set Point Temperature

As highlighted in previous sections, cooling takes up on average 70% of the energy used in residential buildings in Saudi Arabia. Increasing set point temperatures by each degree leads to a reduction in the energy consumption of the HVAC System. As highlighted by (Fasiuddin, Budaiwi, & Abdou, 2010), in their study raising the set point temperature of HVAC systems in commercial buildings in eastern province Saudi Arabia from 21◦C to

23◦C resulted in the reduction of energy consumption by 6.5%. Furthermore, (Dubey et al., 2016) presented that setting the cooling set point temperature at 26◦C in residential buildings will reduce energy consumption by 15.1% in residential buildings in Riyadh. Hence, cooling set point temperatures should be optimized based on occupant comfort and taking into consideration energy consumption. Unfortunately, in Saudi Arabia set point temperatures are set at very low values resulting in extra cooling which leads to increased energy consumption.

2.4.2 Using Energy Efficient Housing Appliances

Housing appliances such as refrigeration units, washing machines, computers, electric stoves, microwaves, television sets and others all contribute to the energy consumption of the houses. If these appliances are outdated and old they will consume extra unnecessary energy due to the inefficiencies. Therefore it is recommended that all equipment in hoses be certified by energy star rating. Energy star is a rating system which defines the efficiency of appliances based on a rating system. The rating system is based on stars and the more stars an equipment has the more it energy efficient it will be. A similar system is adopted in Saudi Arabia by the Saudi Energy Efficiency Center (SEEC) which has specified the minimum energy efficiency standards for home appliances (SEEC, n.d.). Investing in replacing old appliances to new ones will lead to energy savings in homes as portrayed by (Abd-ur-Rehman et al., 2018) in their study. They found that energy star rated appliances reduce energy consumption in residential buildings by 27% in their case study. Hence, investing in energy efficient appliances can be an effective and low cost EEM.

2.4.3 Replacing Conventional Lights with LED

Lighting systems in homes are one of the major energy consuming aspects required to illuminate spaces. The type of light used can determine the amount of energy usage dedicated to lighting systems. Mainly three types of common lighting types are present, incandescent, fluorescent, and recently the introduction of LED lights. Among three, LED lights offer the highest energy efficiency as they emit light in very narrow wavelengths. Furthermore LED lights last longer than the other two types of lights (Richards, 2015). Common households in Saudi Arabia have yet to adopt LED lights and are still relying on the other two types. It was found by (S. N. J. Al-Saadi, Al-Hajri, & Sayari, 2017) in their study in Oman that LED can lead to a reduction of 39% on the lighting load. Therefore, homes in Saudi should consider replacing existing lights with LED lights.

2.4.4 Applying Window Shading

In a country with high solar radiation, it is appropriate to minimize the Solar Heat Gain Coefficient (SHGC) of windows to minimize direct gains which contribute to increase in cooling demand and as a result higher energy consumption. Installing shading devices outside of windows affects reduces the SHGC as it blocks the solar radiation from entering the building and thus reducing energy consumption. Most homes in Saudi Arabia are not using shading devices due to aesthetics or financial reasons. However, a study by (Aldossary et al., 2014) highlighted the importance of adding horizontal shading devices as they significantly reduce energy consumption, hence existing homes should have horizontal shading devices be built on top of the windows.

2.4.5 Improving Glazing Type

Improving glazing type also has an effect on the SHGC similar to window shading. The glazing type can be improved by replacing the conventional single glazed windows with double glazing which have a lower u-value. Double glazed windows can also be insulated with gas filling which in turn reduces the u-values more (Ander, 2016). Current construction methods in Saudi Arabia use single glazing windows mainly as it is a cheaper investment option. However, it is highlighted in a number of studies that incorporating double glazing can lead to significant energy savings (Al-Ashwal, Nagib & Budaiwi, Ismail, 2011) (Taleb & Sharples, 2011) (Alaidroos & Krarti, 2015) (Ghabra et al., 2017). Therefore, it is necessary to replace existing single glazing with double glazing in residential buildings.

2.4.6 Improving Air Tightness

Air tightness of a building is measured by the air infiltration rate or Air Change/hour (AC/h). A high infiltration rate means that outside air is leaking in to the building. This can be due to thermal bridges, leakages in windows and doors and other leakage sources. In a country such as Saudi Arabia with a hot climate, a high infiltration rate means that unwanted hot air from outside is entering the building and thus the HVAC system has to do more effort to reduce the indoor air temperature. Thus, more energy is consumed. Residential buildings in Saudi Arabia have high infiltration rates due to poor construction and studies have indicated that seal air leakage sources can result in significant energy savings. (Dubey et al., 2016) found that reducing air infiltration in residential buildings in Riyadh, Saudi Arabia by 25% can reduce overall energy consumption of a home by 3.2%. Hence, improving air tightness is a key EEM for retrofitting existing buildings.

2.4.7 Using More Efficient HVAC System

As stated in previous section, Saudi Arabia is a country where cooling demands are high and almost 70% of the energy consumed in residential buildings is by the conventional HVAC systems (Said, Habib, & Iqbal, 2003). Having an HVAC system with a low Coefficient of Performance (COP) results in higher energy consumption (Al-Shaalan, 2012). Typical residential homes in Saudi Arabia have low cost HVAC installed but these are very inefficient. It was found by (Dubey et al., 2016) that using an HVAC system with a COP of 5.2% can reduce energy consumption by up to 36% in a home in Riyadh, Saudi Arabia. Thus investing in more efficient HVAC systems will lead to reduced energy consumption and is a key EEM for energy retrofitting existing homes.

2.4.8 Adding Envelope Insulation

Building envelope is the major source of heat gain in buildings and should be properly thermally insulated to minimize heat gain as much as possible and thus reduce energy consumption. Improving envelope insulation is the most common and preferred type of implemented EEM (Al-Widyan & Al-Oqla, 2014) as supported by (Suárez & Fernández-Agüera, 2015) who state that irrespective of climate zone, most energy retrofitting actions focus on improving the thermal insulation of the thermal envelope. In Saudi Arabia, properly insulating buildings is absolutely necessary as buildings are exposed to high amounts of solar radiation. Thus implementing different insulation techniques has been studied extensively in all building types in Saudi Arabia (Budaiwi, Abdou, & Al-Homoud, 2013) (Al-Homoud, 2004). However, including insulation has only recently been made mandatory in Saudi Arabia and residential buildings built before that are having no insulation and thus consuming abnormally high amounts of energy. Many researchers have proposed different envelope details incorporating insulation for residential buildings in Saudi Arabia and have highlighted the saving possible if insulation is used (Alaidroos & Krarti, 2015) (Ghabra et al., 2017) (S. N. Al-Saadi & Budaiwi, 2007). Therefore, exiting uninsulated wall should be insulated and have to be an integral part of retrofitting existing buildings in Saudi Arabia.

2.5 Using Building Information Modelling (BIM) to Retrofit Existing Buildings

BIM can be defined as “Building Information Modelling is digital representation of physical and functional characteristics of a facility creating a shared knowledge resource for information about it forming a reliable basis for decisions during its life cycle, from earliest conception to demolition”(Mordue, n.d.). It is widely known that BIM offers multiple advantages to the construction industry such as the adoption of an Integrated Design Process (IDP), however recently the capabilities of BIM have expanded including retrofitting existing buildings and maintenance of buildings as well (Ilter & Ergen, 2015). Adoption of BIM to retrofit existing buildings is currently an undeveloped area and the research present currently is premature. As highlighted by (Zuo & Zhao, 2014) using BIM to retrofit existing buildings is a trending research issue and has been stressed by researchers as the new direction towards retrofit studies. This shift of retrofit studies towards using BIM is due to the numerous advantages and savings which can be achieved if BIM is implemented properly. However implementing BIM effectively in retrofit projects is a complex task and a proper framework is required for successful adoption of BIM (Okakpu et al., 2018). Researchers are currently investigating and proposing frameworks for the adoption of BIM to retrofitting and maintenance of existing buildings (McArthur, 2015) (Khaddaj & Srour, 2016).

One of the most comprehensive framework is presented by (Sanhudo et al., 2018) as seen in figure 8. They have categorized the framework into four main sections including data acquisition, modelling, interoperability, and building energy analysis. All of these areas need to be extensively investigated through the use of case studies and this is the direction of the latest retrofit research studies.

As stated earlier, investigating BIM adoption to retrofit existing buildings is currently a developing and trending research issue globally and successful implantation through the use of case studies need to be presented in future research work. Similar is the case in Saudi Arabia, where only one study is present which utilized BIM to investigate the effects of thermal insulation on existing residential buildings (Al kanani, Dawood, & Vukovic, 2017). However, there is a need for more comprehensive and holistic research studies which study the use of BIM in retrofitting existing buildings in Saudi Arabia.

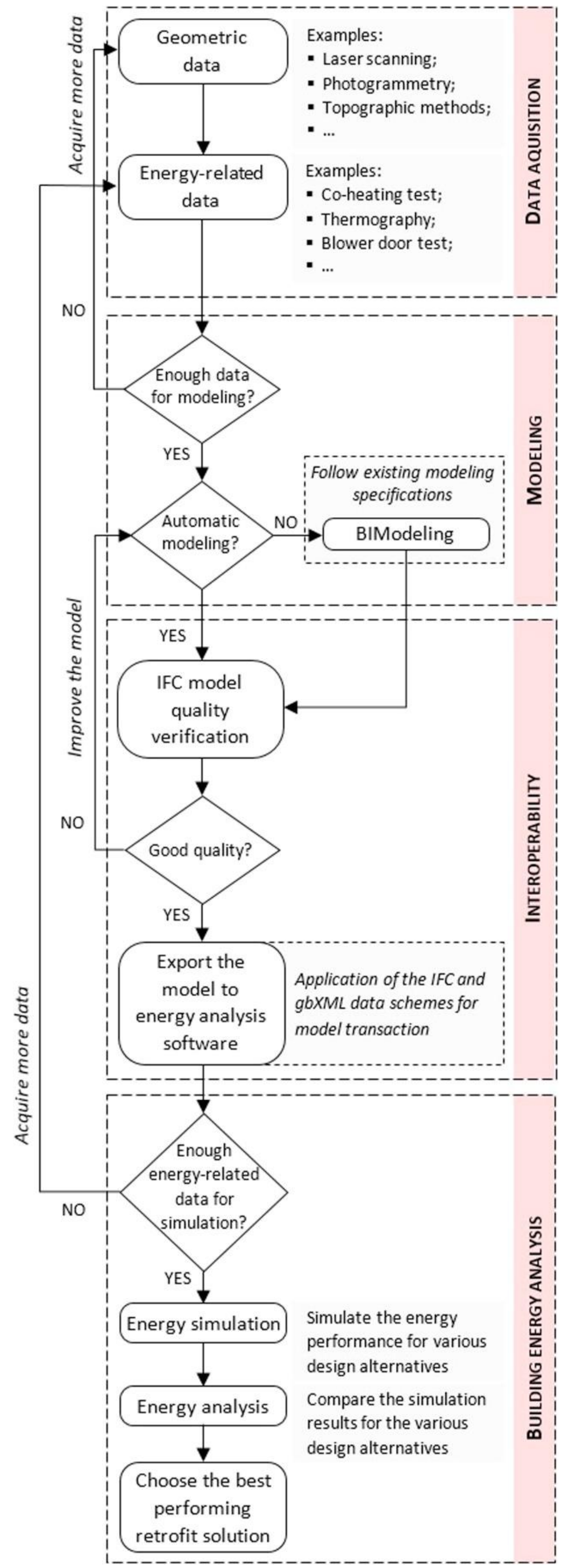


Figure 8: BIM-based Framework for Energy Retrofitting Proposed by Sanhudo et.al.

Source: (Sanhudo et al., 2018)

2.6 Policies, Barriers and Incentives of Energy Retrofitting

Retrofitting has some certain barriers identified by researchers. Researchers (Kmeťková & Krajčík, 2015) have categorized these barriers into 3 categories. 1) Financial Barriers, 2) Technical Barriers, 3) Administrative Barriers. The financial barriers include high initial investment for retrofitting, owners not considering payback and lack of funds and inability to secure finances. (Achtnicht & Madlener, 2014) also emphasize on lack of financial resources as a major barrier. The technical issues include shortage of material, lack of human resources (skilled), and lack of quality control. Ownership of the buildings is considered the administrative barrier as some apartment buildings have different owners for each apartment. Some of these barriers can be overcome by initiatives or incentives set by the government for owners or tenants of apartment buildings. Incentives have been implemented by the European Commission in order to regulate the investments in energy efficient solutions in commercial and residential buildings. In addition to EU members, countries including USA, New Zealand, Italy, South Africa, Australia, Russia, Mexico, South Korea, China, Japan, Canada all have some sort of energy efficiency programs with incentives and measures in place (AlFaris et al., 2016)

An example of policy incentives in South Korea is when policy makers, developers and residents in South Korea debated whether to demolish or refurbish old apartments and the decision makers proposed energy efficient refurbishment of old apartment buildings. The South Korean government introduced incentives such as permitting developers to increase the number of floors on top of apartment buildings in case of refurbishment (Jang, Jones, & Kang, 2015). Furthermore, Canada introduced an incentives program for homeowners wanting to audit their houses and upgrade for energy efficiency. The program called EnerGuide for Houses (EGH) was introduced in April 1998 and was ended in May 2006 provided incentivized home auditing services which also recommended homeowners on potential methods to improve energy efficiency. (Gamtessa, 2013) evaluated the effectiveness of the program and stated that programs such as this one are important to improve energy efficiency in old high energy use homes owned by low income users. Additionally in Germany (Weiss, Dunkelberg, & Vogelpohl, 2012) have listed several incentive programs including KfW program for Energy Efficient Renovation which gives low interest loans and other subsidies to homeowners. Another program called the Market Incentive Program (MIP) focuses on providing subsidies for solar panels, biomass collectors and heat pumps.

As seen from the examples, policy incentives can be introduced to drive energy retrofitting in the residential sector. Saudi Arabia currently has no policy incentives and an incentive plan is necessary which takes into account the local challenges as discussed in section 2.1.

2.7 Economic Analysis Methods

A popular and well established method among researchers to calculate the complete costs associated with buildings is the Life Cycle Cost Analysis (LCCA). According to (Fuller, 2016) when design team has to choose between different alternatives for a facility a LCCA is conducted of all the different alternatives to make sure the alternative with the lowest overall cost is selected. The benefit of LCCA is that it gives an economic overview for the whole life of the building and not the initial cost only and thus an alternative with high initial cost and lower life cycle cost, as it saves on energy costs, can be selected. Therefore numerous researchers have adopted this method for economic analysis in their studies. (Bogenstätter, 2010)'s study titled "prediction and optimization of life-cycle costs in early design” states that alternatives have to be selected based on an optimization analysis which considers LCCA.

There are several methods which can be adopted to perform economic analysis for EEM alternatives including Net Present Value (NPV), Annual Worth (AW), Simple Payback period (SPP), Discount Payback Period (DPB), Internal Rate of Return (IRR), and Profitability Index (PI). To assess the economic viability in in energy retrofit studies, comparing NPV is the most common and effective method. In NPV method, all the costs in the lifecycle of the building over a period of time are brought to the present value and compared as done by (Leal, Granadeiro, Azevedo, & Boemi, 2014) in their retrofit study.

To conclude, economic analysis for the proposed EEMs is required to optimize the proposed EEMs implementation plan. LCCA and specifically comparing the NPV of each proposed retrofit plan is the best way to assess the economics of the different EEMs as it provides economic impact over the lifetime of the proposed EEMs, hence NPV will be used for the economic assessment of this study.

CHAPTER 3

Research Methodology

This chapter discusses the methodology (Fig.6) of the research work conducted including BIM framework, case studies and analysis methods. Firstly, adoption of the BIM based framework is discussed. Next, two prototypical models were developed as case studies for a villa and an apartment building for the region. All information specific to the case studies are presented including architectural details, envelope construction, occupancy schedules, electrical equipment, and HVAC systems. Application of BIM is also presented and finally energy, economic and environmental analysis methods are discussed.

3.1 BIM Based Framework for Energy Retrofitting of Existing Buildings

Retrofitting existing buildings has been extensively investigated in literature globally. However, most of the studies have followed a traditional framework to retrofit existing buildings in which energy analysis of a case study is conducted using an energy analysis software. There is no consideration for the design and building specific related data changes which occur to a building as a result of the retrofit.

A BIM based framework offers much more too retrofitting existing buildings and is currently being investigated extensively as an improved method of retrofitting existing buildings. As stated earlier, the research work in this area is currently premature and many areas need to be researched upon. This study has adopted a BIM based framework to retrofit existing residential buildings in Saudi Arabia.

A BIM based framework can be divided into three main parts including data acquisition, BIM modelling, and energy analysis. Each of these parts can be implemented using several methods of application. However, not all of the application methods for each part have been investigated and still need to be researched upon. Furthermore, the framework has to be customized to fit the location specific challenges and needs. For example, data acquisition of existing buildings can be easily done through obtaining documentation of existing buildings, however, in Saudi Arabia documentation is not available for most buildings and if it is available it is not accurate enough. Hence, other methods such as laser scanning and photogrammetry need to be investigated.

Figure 9 summarises the main application methods within each part of the BIM based framework. Due to the wide scope and range of application methods, the framework implementation is limited in this study to certain application methods in this study. In the data acquisition part, building documentation was used to develop the building geometry and electricity bills were used for the energy data. Furthermore, Autodesk Revit software was used a BIM application tool as this tool is the most widely accepted by the construction industry in Saudi Arabia. The last part which is energy analysis part can be performed in three ways, using cloud, plug-ins or external software. The best method in terms of ease of use and accuracy is not determined currently. In this study, an external software was used and the other two methods are not investigated.

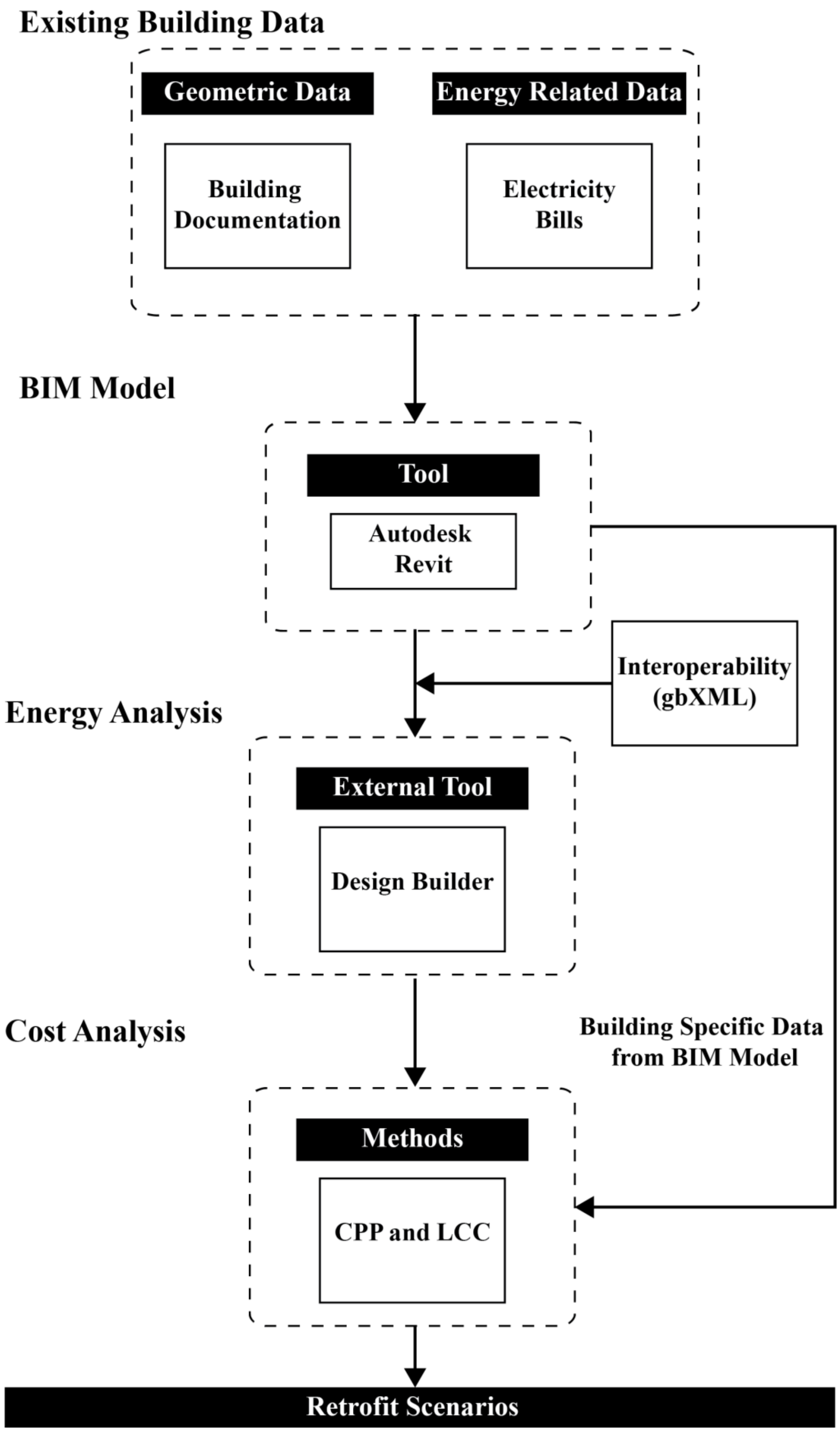


Figure 9: BIM Based Framework to Retrofit Existing Buildings

3.2 Case Studies

A case study of a villa and an apartment building were used to study the implementation of the retrofit plan. Using prototypical models is a very common method to investigate EEMs and develop energy retrofitting plans as seen in chapter 2. The two case studies are described below.

3.2.1 Case Study 1 - Villa

A prototypical house was developed based on the survey by (Alrashed & Asif, 2015b). The model is a single family detached house known as a 'villa' of 2 floors. This type of dwelling represents 40% of the Saudi residential building stock (Ahmad, 2004). Specific details about the house can be seen in table 2.

The villa has primarily lounges/guest sitting areas and kitchen on the ground floor and private spaces including bedrooms and other private miscellaneous spaces on the first floor as seen in the floor plans (Fig.10). The total floor area of the house is 430 Sqm and occupancy is assumed to be 7 people. The villa also has typical Saudi house style architecture and aesthetics as seen in the developed elevations in figure 11. This spatial arrangement is a very common arrangement in the existing Saudi homes.

Building Envelope Details

The external walls of the villa are typical sections which were used in construction of the houses. The wall section has no thermal insulation and is made up of concrete blocks with a stucco finish. The total thickness of the wall section is 25 cm and the U-value of the wall is computed to be 2.23 W/Sqm-K. The finish color of the walls is a beige-yellow color.

The roof of the house is 42 cm thick and made up of 6 primary layers including a terrazzo finish, waterproofing layer, concrete structure and interior gypsum finish. The U-value of the roof is calculated to be 1.934 W/Sqm-K.

Window to wall ratio is around 11% overall and typical rectangular windows are used in most spaces. There is no external window shading in place. The glazing system is a single clear glass which was typically used in construction. It has a U-value of 6.1 W/Sqm-K.

HVAC Details

The most common type of HVAC systems in until recently is the Window A/C. A typical window A/C of 2 tones is selected which has a COP of 1.5. A total of 12 A/C units are present in the case study, mostly one in each room.

Table 2: Villa Case Study Detail Description

Element	Description
Orientation	East - West
Shape	Square
Occupants	7
Floor Height	3.4 m
Total Floors	2
Total Built Area	430 Sq.m
Exterior Walls	25mm stucco,75mm concrete block,50mm Air Gap,75mm concrete block,25mm stucco, U-value: 2.23 W/Sqm-K
Finish Color	Beige-Yellow
Interior Walls	25mmstucco,100mm concrete block, 25mm stucco
Roof	25mm terrazzo,25mm mortar,5mm bitumen layer,150mm cast concrete,200mm concrete block,15mm gypsum board U-value: 1.934 W/Sqm-K
Ground Floor	150 mm slab on grade
W-W Ratio	11 %
Glazing	Single Clear, U Value: 6.1 W/Sqm-K
Shading	None
HVAC	Window AC, COP = 1.5, Total Units =12
AC Set point	22◦C
Lighting	Fluorescent, 5 W/Sqm
Equipment	Average gain = 4 W/Sqm
Infiltration	1.2 ac/h (poor construction)
EUI	148.83 kWh/Sqm/Year

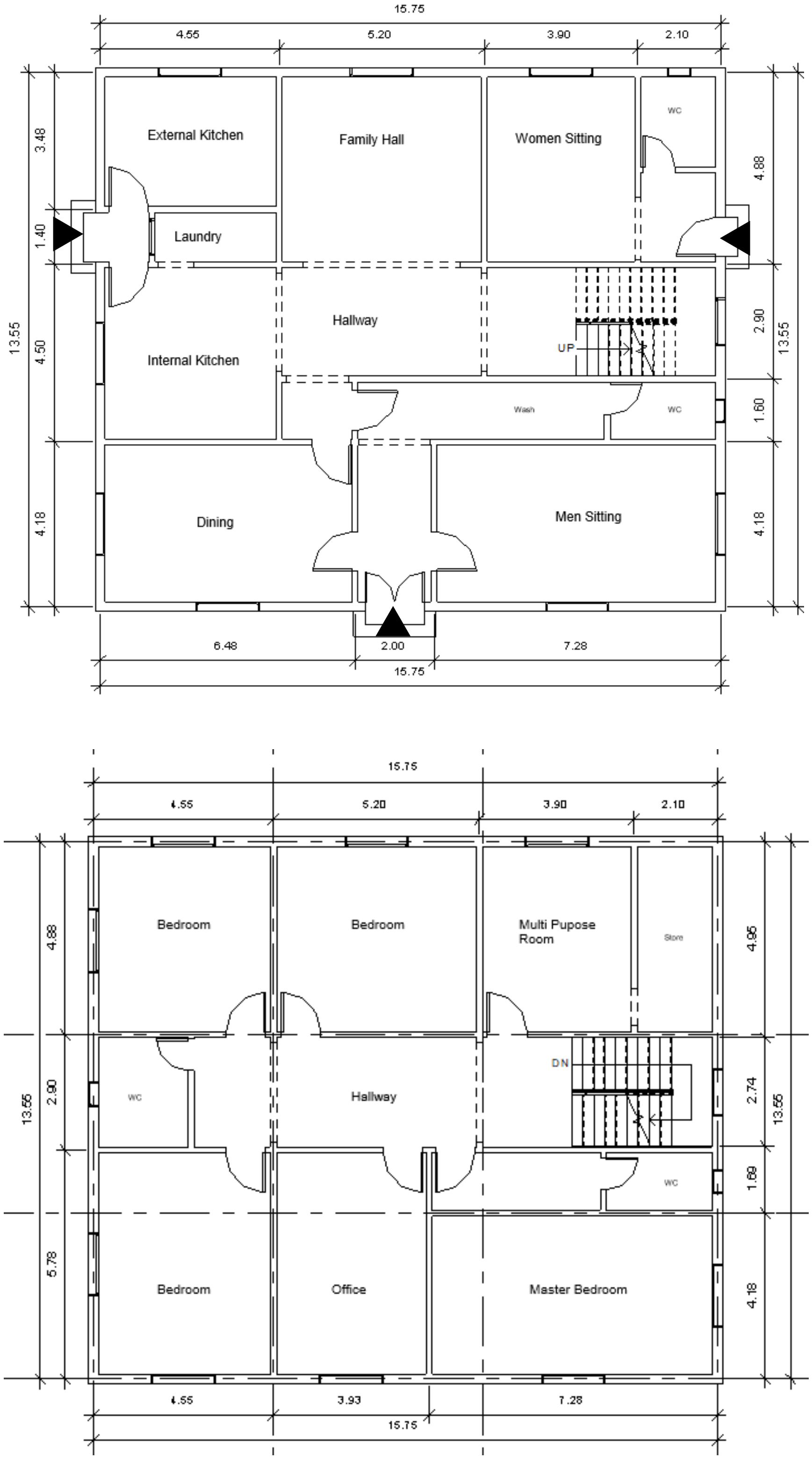


Figure 10: Top: Ground Floor Plan, Bottom: First Floor Plan

Figure 11: Top: East Elevation, Bottom: North Elevation

3.2.2 Case Study 2 - Apartment

A prototypical apartment building model was developed based on the survey by (Alrashed & Asif, 2015b) and in addition personnel gathered data. The model is a multi-family apartment building of 3 floors with 2 apartments per floor. This type of dwelling represents 35% of the Saudi residential building stock (Alaidroos & Krarti, 2015). Specific details about the building can be seen in table 3.

Each apartment in the apartment building has primarily lounges and guest sitting areas on one side of the plan and kitchen and private spaces including bedrooms and living on the other half as seen in the floor plans (Fig.12). The total floor area of one apartment is 120 Sqm while the floor are for one flor is 260 Sqm including circulation. Thus the total built up are of the apartment building is 780 Sqm. The designed occupancy of each apartment is 4 and thus a total of 6 apartments will result in a total of 24 people in the whole building. The apartment also has typical Saudi house style architecture and aesthetics as seen in the developed elevations in figure 13.

<u>Building Envelope Details</u>

The envelope construction of the apartment does not differ from the villa as typical construction details were used in the construction of both residential buildings. The wall section has no thermal insulation and is made up of concrete blocks with a stucco finish. The total thickness of the wall section is 25 cm and the U-value of the wall is computed to be 2.23 W/Sqm-K. The finish color of the walls is a beige-yellow color.

The roof of the house is 42 cm thick and made up of 6 primary layers including a terrazzo finish, waterproofing layer, concrete structure and interior gypsum finish. The U-value of the roof is calculated to be 1.934 W/Sqm-K.

Window to wall ratio is around 8% overall and typical rectangular windows are used in most spaces. There is no external window shading in place. The glazing system is a single clear glass which was typically used in construction. It has a U-value of 6.1 W/Sqm-K.

HVAC Details

Similar to the Villa, most common type of HVAC systems in use in apartments until recently is the Window A/C. A typical window A/C of 2 tones is selected which has a COP of 1.5. A total of 6 A/C units are present in each present with a total of 36 units in the whole apartment case study.

Table 3: Apartment Case Study Detail Description

Element	**Description**
Orientation	East - West
Shape	Rectangular
No. of Apartments	6
Occupancy	4/Apartment. Total = 24
Floor Height	3.3 m
Total Floors	3
Total Built Area	780 Sq.m
Exterior Walls	25mm stucco,75mm concrete block,50mm Air Gap,75mm concrete block,25mm stucco U-value: 2.23 W/Sqm-K
Finish Color	Beige-Yellow
Interior Walls	25mmstucco,100mm concrete block, 25mm stucco
Roof	25mm terrazzo,25mm mortar,5mm bitumen layer,150mm cast concrete,200mm concrete block,15mm gypsum board U-value: 1.934 W/Sqm-K
Ground Floor	150 mm slab on grade
W-W Ratio	9 %
Glazing	Single Clear, U Value: 6.1 W/Sqm-K
Shading	None
HVAC	Window AC, COP = 1.5
AC Set point	22◦C
Lighting	Fluorescent, 5 W/Sqm
Equipment	Average gain = 4 W/Sqm
Infiltration	1.2 ac/h (poor construction)
EUI	180.53 kWh/Sqm/Year

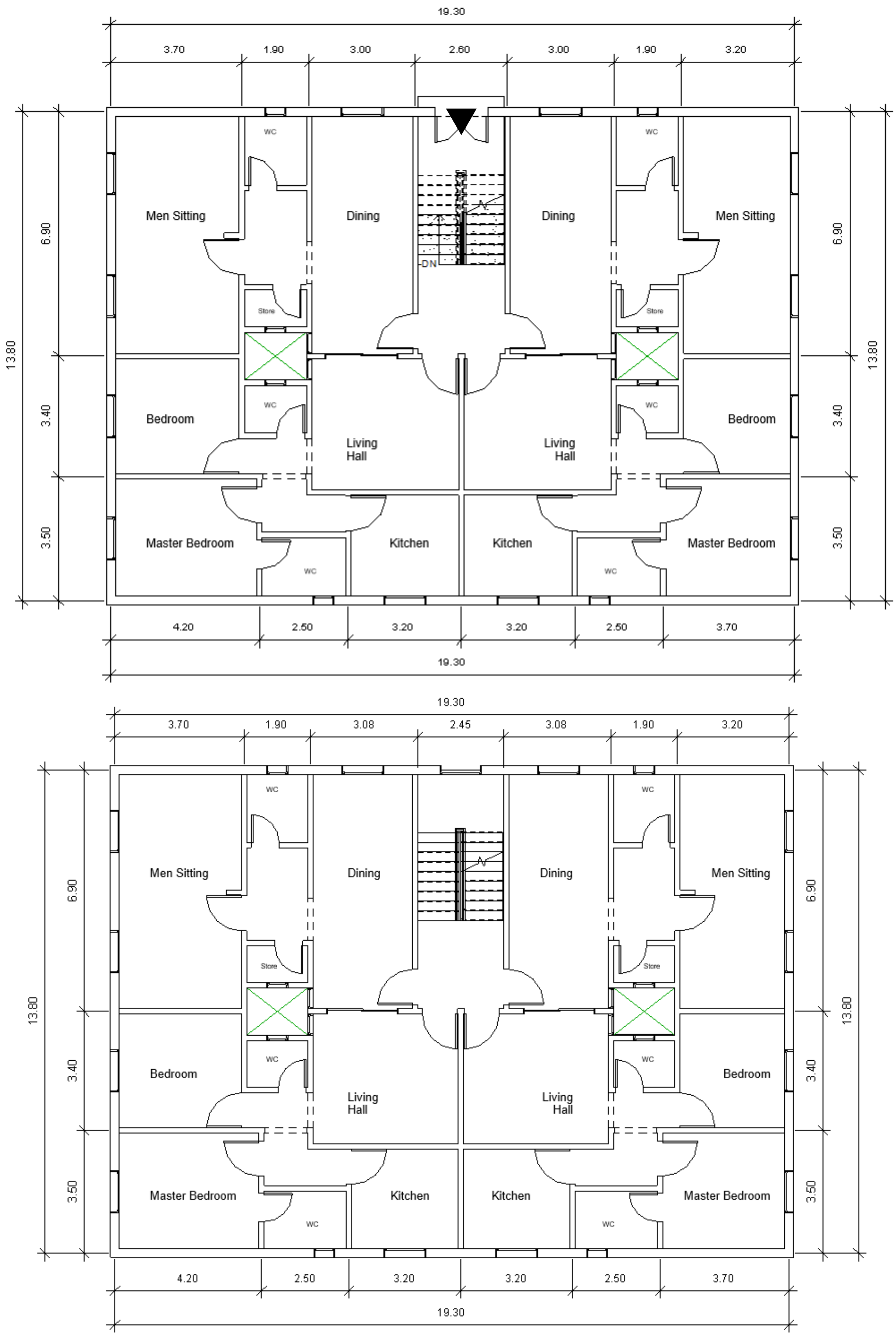
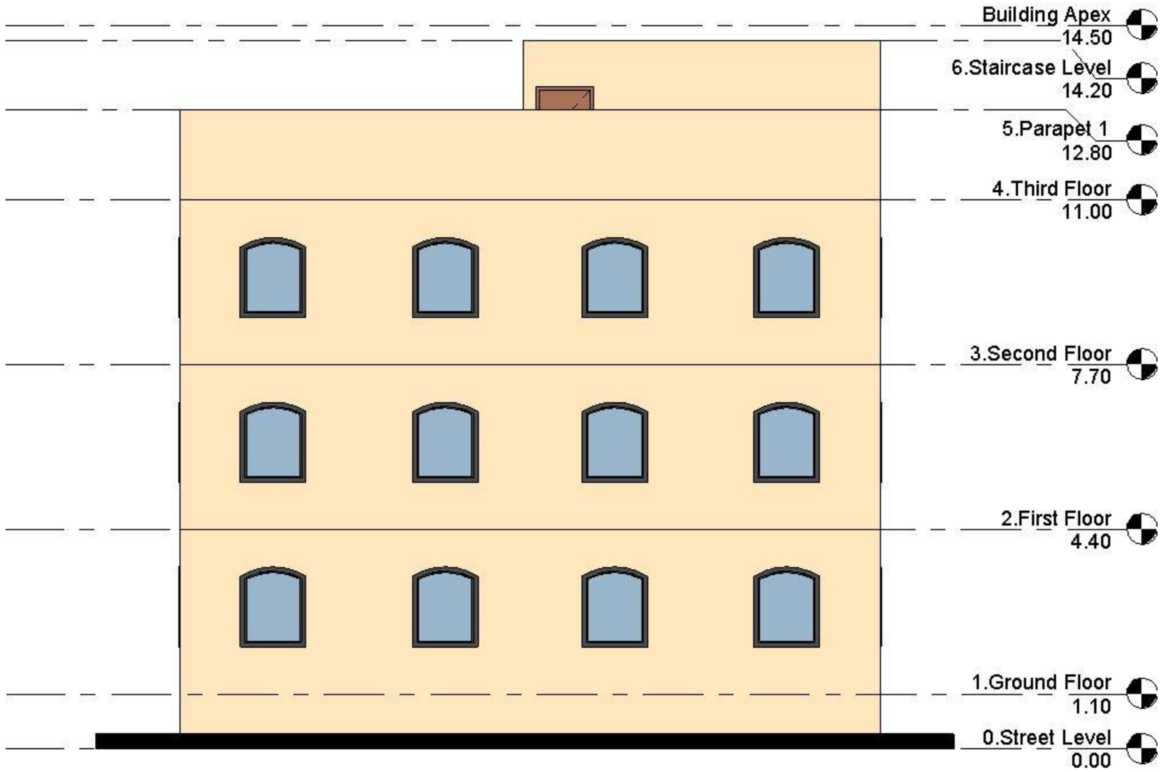


Figure 12: Top: Ground Floor Plan, Bottom: Typical Floor Plan



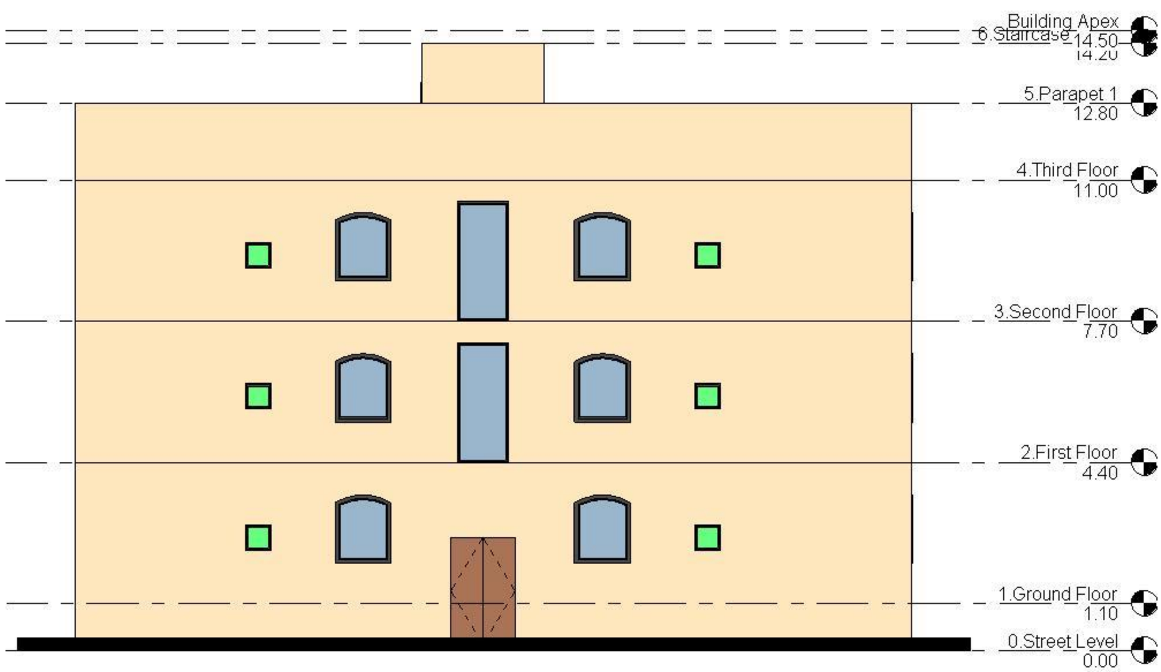


Figure 13: Top: East Elevation, Bottom: North Elevation

3.3 Building Information Model (BIM) Development and Application

This section discusses the application and use of BIM in retrofitting existing buildings using the case studies. The limitations however are that the framework presented in figure 8 to retrofit existing buildings using BIM is a complex framework requiring a collective effort of a team with a variety of skills. Hence, in the following sections, the case studies are used to investigate the limited application of the framework in Saudi Arabia.

3.3.1 BIM Model Development

BIM models of the two case studies were developed in Autodesk Revit 2017. Revit is a BIM application software by Autodesk which with architectural, structural and MEP systems design capabilities (Autodesk, 2018). Revit provides designers and engineers the ability to design using modelling components, analyse design, generate documentation, interoperability with different software, and create visual 3D images. BIM can be utilized to design and develop new buildings as well as to retrofit existing buildings.

Developing BIM models of existing buildings requires a different set of challenges. For effective and successful use of BIM, existing building models should be accurate and this requires different data capturing techniques. These techniques can be automated such as laser scans which result in automatic development of the 3D model or manual where a detailed building audit is conducted and the BIM model is built based on it. The more detailed the audit, the more accurate the BIM model will be.

One of the main hindrances to BIM application to retrofit existing residential buildings in Saudi Arabia will be the lack of information in existing buildings. Buildings which were built when regulations were not enforced don’t have proper documentation available or if documentation is available it may not be the same as the built case. Therefore, it is necessary to research on effective data capturing techniques in Saudi Arabia for BIM to be successfully implemented.

In this case, information on the level of a preliminary audit was obtained to develop the model. Information such as the envelope details, window types and door types were defined using parametric objects in Revit. The developed BIM models can be seen in the following figures for the villa (Fig. 14) and apartment (Fig.15) case study.

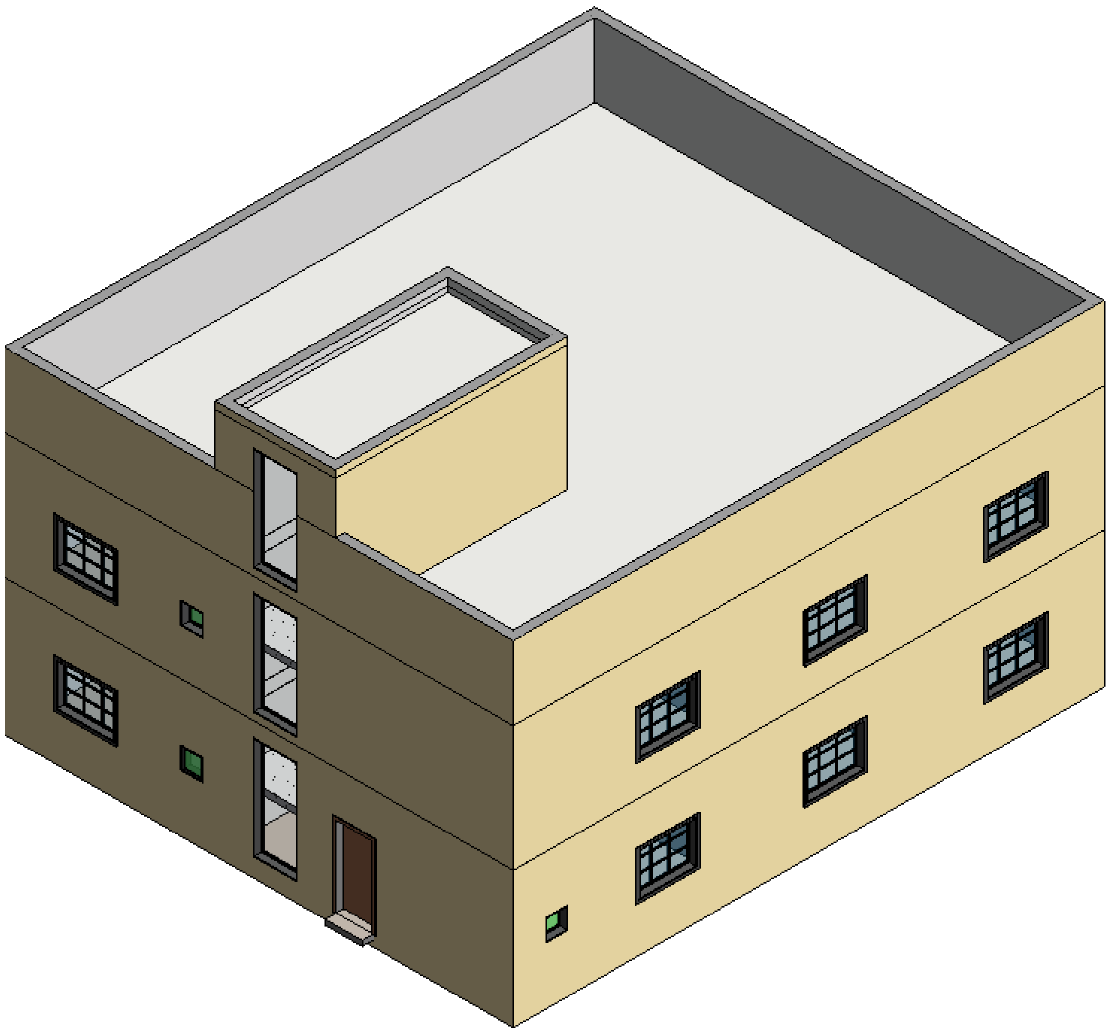


Figure 14: Image of the Villa BIM Model

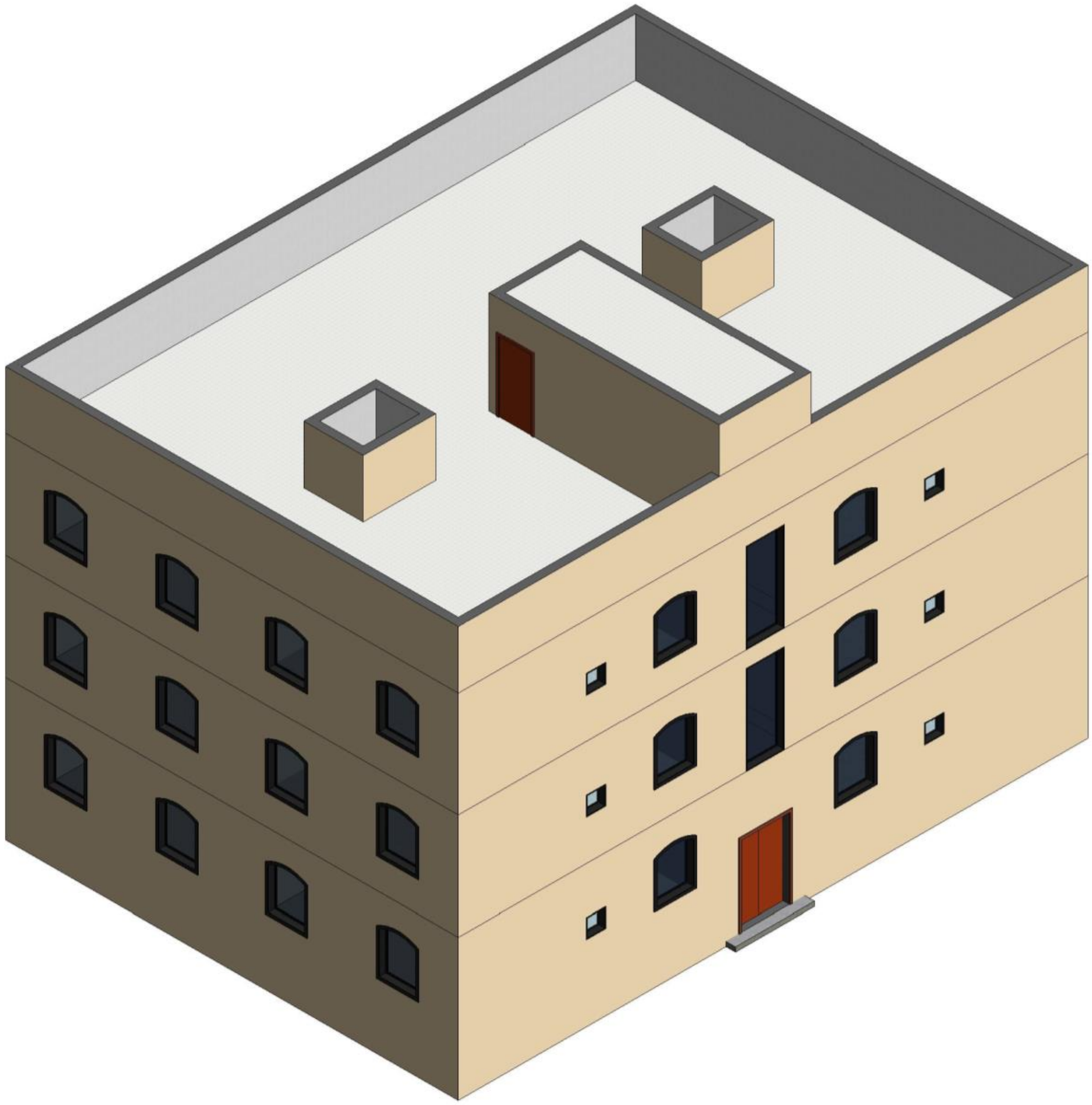


Figure 15: Image of the Apartment Building BIM Model

3.3.2 BIM Application in Retrofitting

The primary ways in which BIM can be effectively used can be categorized in two categories 1) design of EEMs and 2) building specific data. BIM model can be used to design EEMS and as a result visualize the changes which will be caused by the EEMS. As mentioned previously, the indirect EEMs including envelope details, window shading and glazing type are the ones which can be visualized using BIM as these are the only EEMs requiring design change and construction. Furthermore, rooftop PV can be incorporated as well and the roof can be redesigned accordingly to accommodate the PV Panels. The architectural design changes resulting from the application of EEMs can be presented to the clients using the strong 3D visualization tools of BIM.

The villa case study was used to portray the above discussed methods in which BIM can used to retrofit existing Saudi villas (Fig.16). The retrofit design done in Revit visualizes the changes made to the existing building. This is used to assess the architectural design and aesthetics of the building. This can be highlighted more significantly if more changes are incorporated into the BIM model such as if any design alterations are done in terms of change in the overall architectural style, building material, window to wall ratio or any additions made to the architectural plan. Furthermore, it can be used to convince clients who don't want any architectural changes in their buildings but would like to reduce energy consumption that energy retrofitting can be designed to have minimal changes to their building. Such is the case for the villa. The only visible indirect EEMs is window shading while rest of the indirect EEMs don't have much visual change.

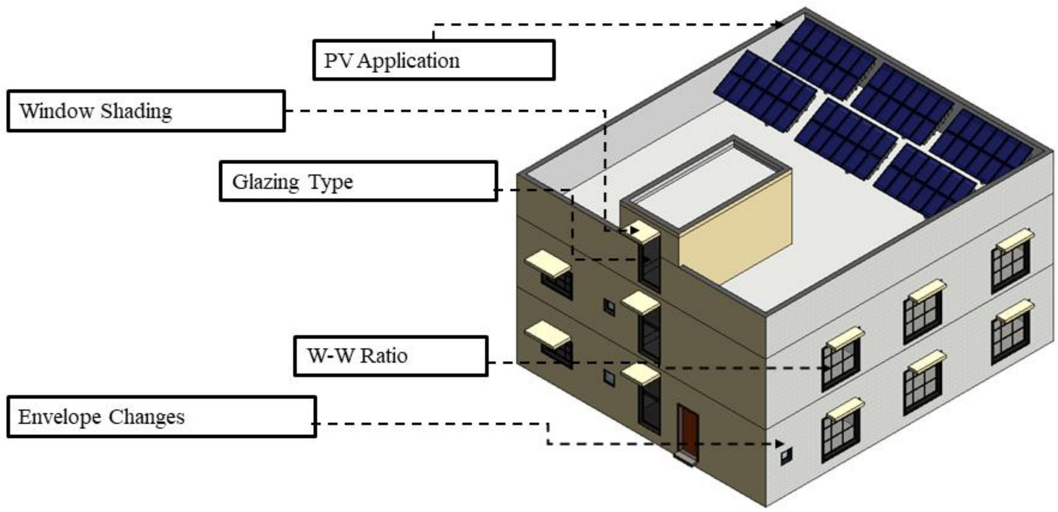


Figure 16: Example of BIM Use in Retrofitting Villa Case Study

Furthermore, through the retrofit design of the house using BIM, all construction related information required to actually make the changes in reality are updated automatically. For example, for the case of the villa, wall material take-off is done after insulation has been added in the retrofit design (Fig. 17). The material take-off information is than used to calculate the time required to add insulation to all the walls, the amount of material required and subsequently the cost associated with making the changes. This building specific data is then used in the economic assessment for both of the case studies.

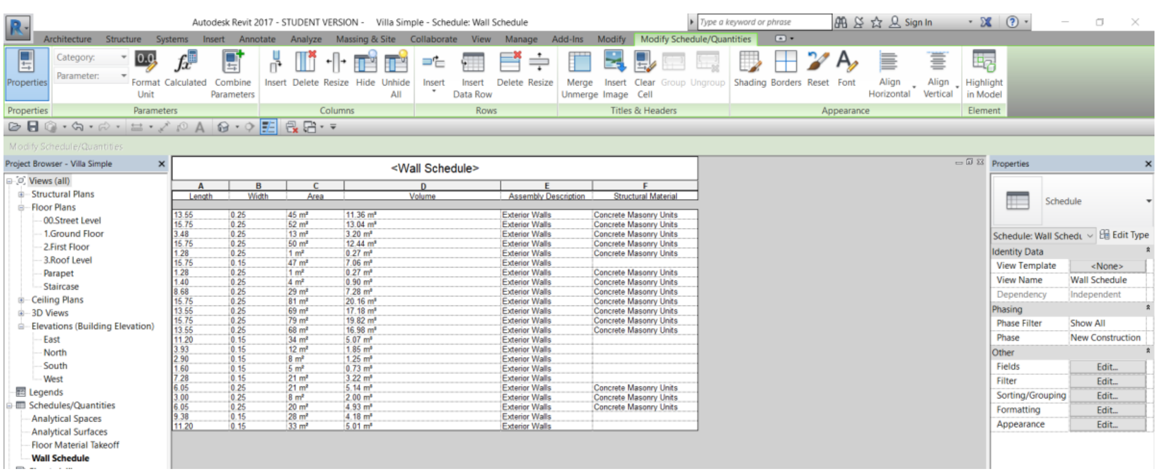


Figure 17: Automatically Generated Villa Wall Schedule in Revit

3.3.3 BIM Interoperability with Building Energy Modelling (BEM)

The next stage in BIM application is to conduct the energy analysis of the case studies. After creating the geometry in Revit, there are 3 methods in which the energy analysis can be conducted. These include either using the in-built green building studio provided by Autodesk, install external plug-ins provided by different software such as IES-VE plug-in or lastly to export the building geometry from Revit and use an external software. The best way to conduct the energy analysis is currently debatable and in extensive research such as the study by who compared the different methods (Aljundi, Pinto, & Rodrigues, 2016).

Similar research should be done for Saudi Arabia and interoperability should be investigated and the best way forward should be presented which is also accepted by the construction industry professionals of Saudi Arabia. In this study, an external software was used to conduct the energy analysis. Firstly an energy analytical model was created from the building geometry for the villa (Fig.18) and the apartment building (Fig.19). The energy analytical model is required to conduct the energy analysis. Next, the developed energy analytical model was exported in gbXML format for energy simulation in DesignBuilder software. gbXML format is developed to increase interoperability between design and various analysis software (Harriman, 2014). The two case studies were successfully exported and imported into the energy analysis software thus indicating that this path of BIM-BEM is successful. However, one of the major drawbacks with this method is that after the implementation and design of each EEM in BIM, the energy analytical model had to be recreated and then re-exported using gbXML format. This will create multiple number of files and is a much disintegrated approach. Thus, it would be much more efficient if energy analysis is conducted within the BIM software itself, however the available energy analysis software for BIM need to be investigated and the results should be verified with existing stand-alone energy analysis software.

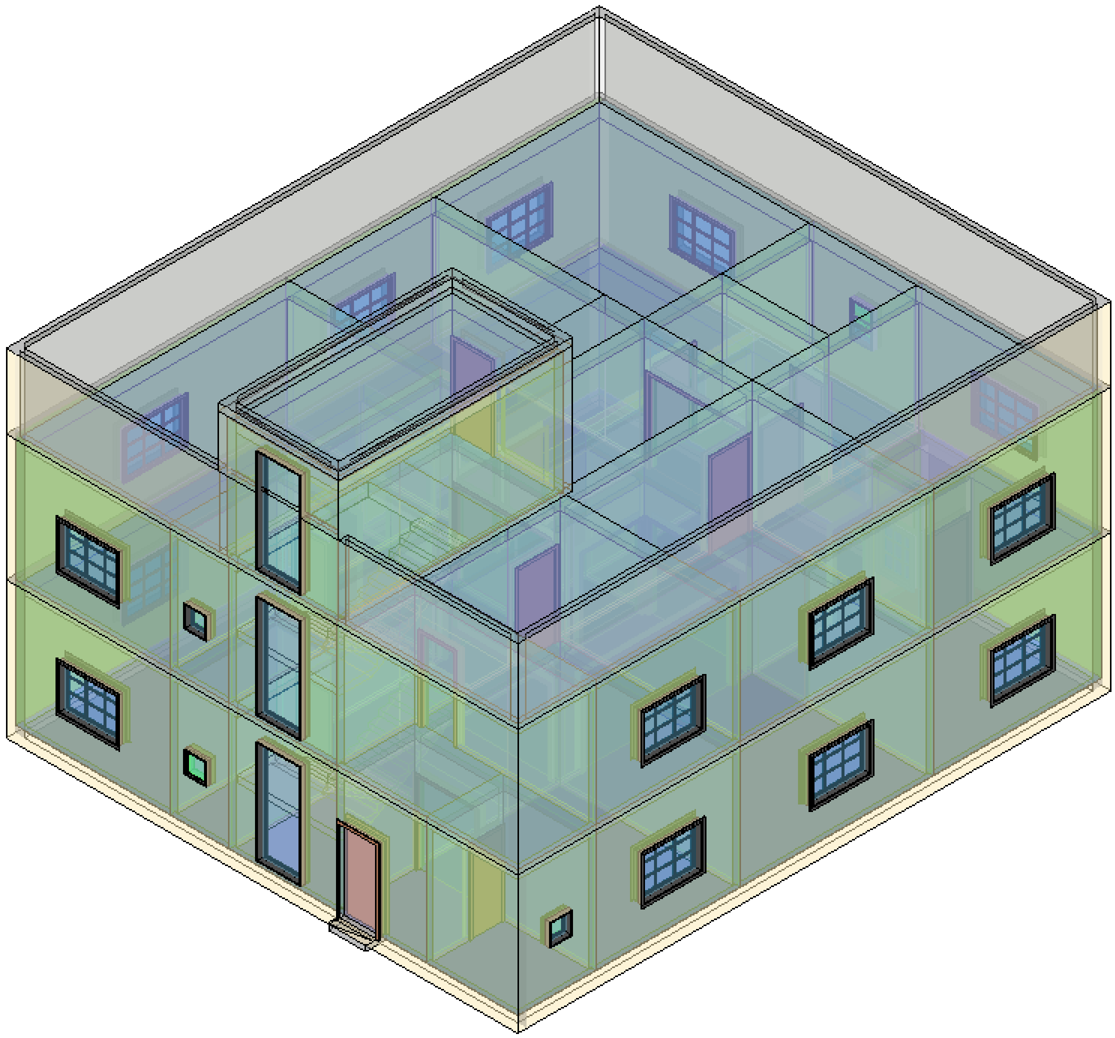


Figure 18: Energy Analytical Model of the Villa

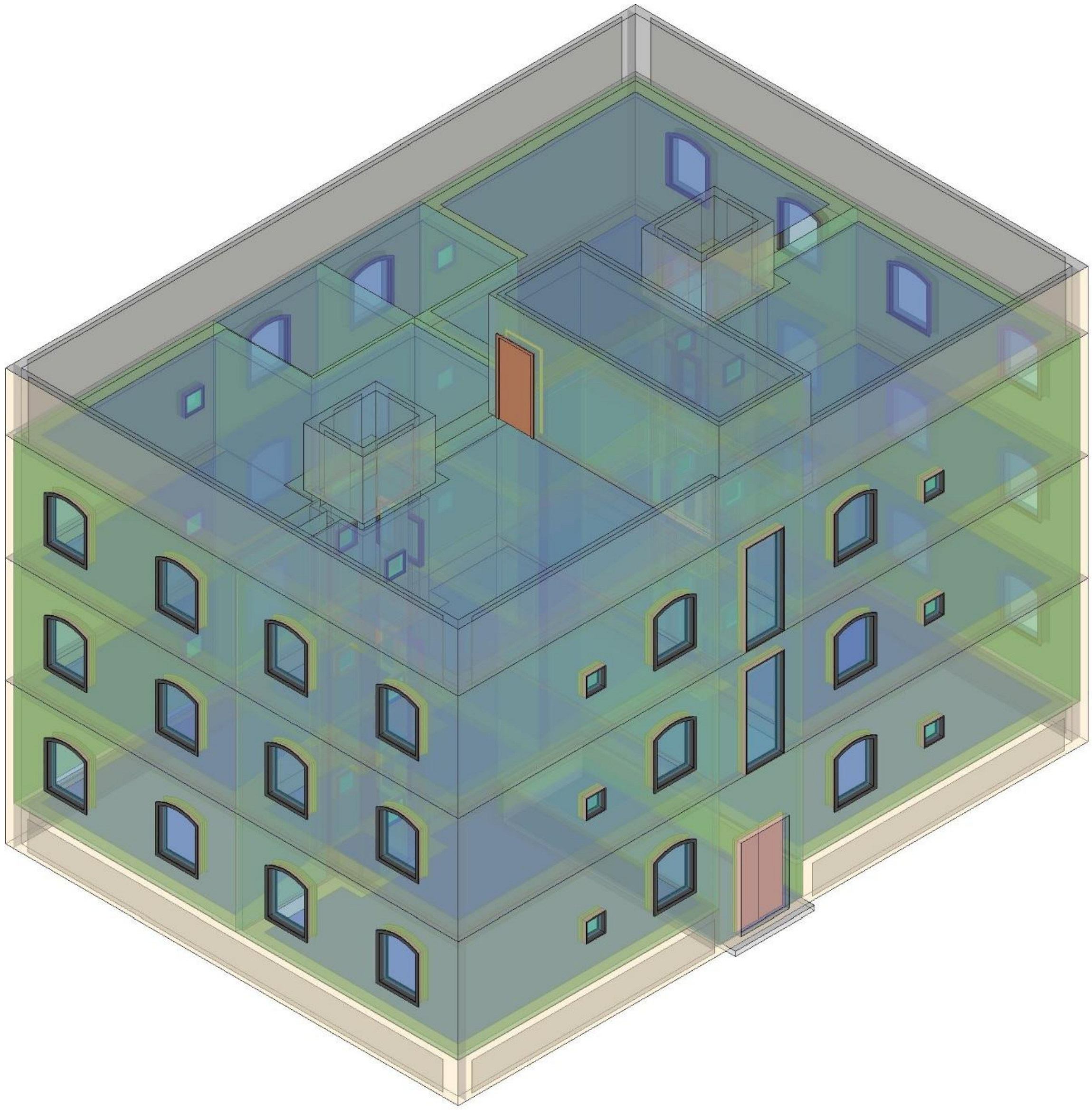


Figure 19: Energy Analytical Model of the Apartment Building

3.4 Building Energy Modeling

DesignBuilder software was used to conduct the energy simulation for the energy analysis. DesignBuilder software uses the EnergyPlus engine for the energy analysis. EnergyPlus is a common engine to perform energy simulation among researchers due to its accuracy.

DesignBuilder provides an easy to use interface of EnergyPlus and is compatible to use with BIM.

The exported gbXML files of the two case studies were imported into DesignBuilder and the results are seen in figure 20 for the villa and figure 21 for the apartment building. Simulations for the energy model were conducted in Dhahran, Saudi Arabia and the weather data provided by EnergyPlus for the location was used.

Physical properties and energy consumption parameters were defined as described in table 2 and table 3 for the villa and apartment respectively. The villa building plan was divided in 3 separate HVAC zones on the ground floor including lounge, kitchen and circulation and into 2 zones on the first floor including bedrooms and circulation. The apartment building is much more complex and each apartment was divided into three thermal zones including bedroom, kitchen and lounge areas. Hence, each floor of the apartment building was divided into six thermal zones. The cooling temperature of the HVAC was set at 22°C. Other model information including occupancy schedules, equipment loads and Domestic Hot Water (DHW) were adopted from literature (Alaidroos & Krarti, 2015) (Ahmad, 2004) (Alrashed & Asif, 2015b).

The energy simulation was conducted for the base case, after implementation of each EEM, and for the three levels of the retrofit plan. The results were compared using the Energy Use Index (EUI). The EUI is a measure of the energy consumption of a building in one year relative to the area of the building and is defined in kWh/Sqm/Yr. Thus, the EUI is used to compare different alternatives.

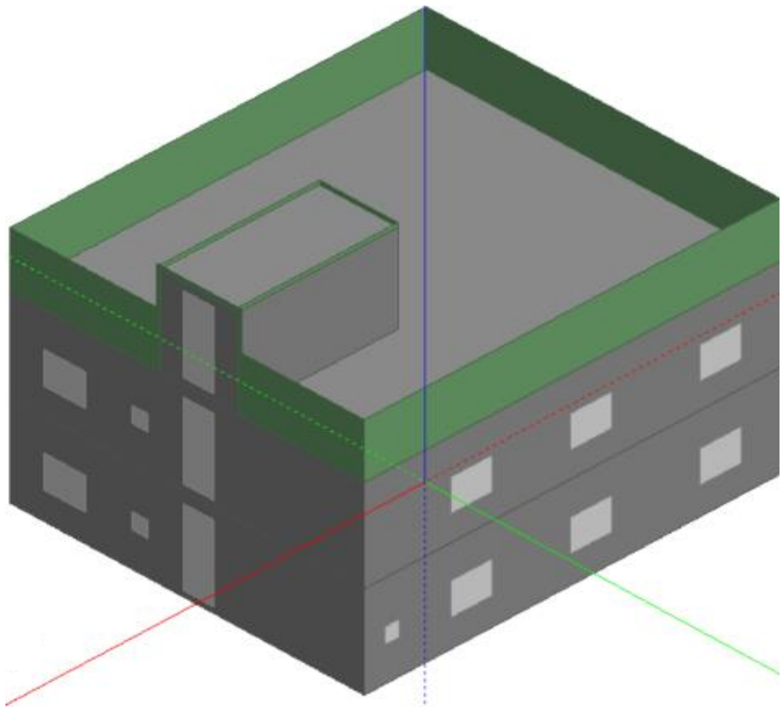


Figure 20: Energy Model of the Villa in DesignBuilder

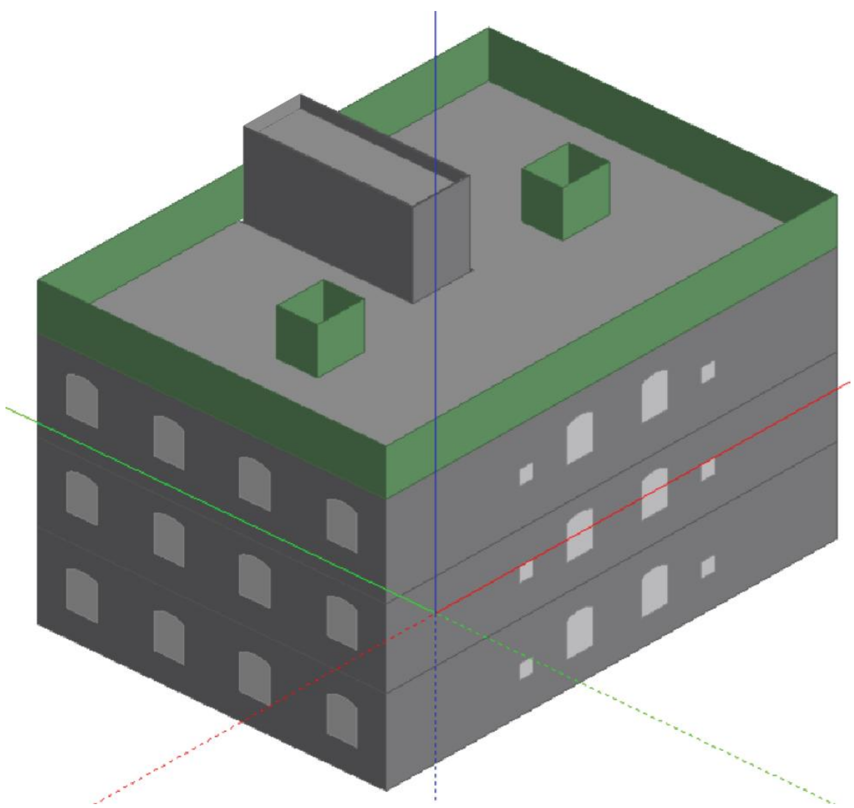


Figure 21: Energy Model of the Apartment Building in DesignBuilder

3.4.1 Case Studies Model Calibration

Calibration of the two energy models was done by comparing the simulated energy consumption with the consumption of two case studies as defined by (Alrashed & Asif, 2015b). In actual, the villa consumes 64,000.16 kWh of electricity per year which translates to an energy use index of 148.83 kWh/Sqm/Yr. Houses in the region typically have a EUI within this range and it was found by (Alrashed & Asif, 2014) that villas in the region on average consume 150 kWh/Sqm/Yr. The simulated model has an Energy Use Index (EUI) of 146.1 kWh/Sqm/Yr, which is a difference of almost 2% from the actual consumption (Fig. 22). Regarding the end-use energy consumption, 71% of the energy consumption is required for cooling purposes which is an expected result (Fig.23).

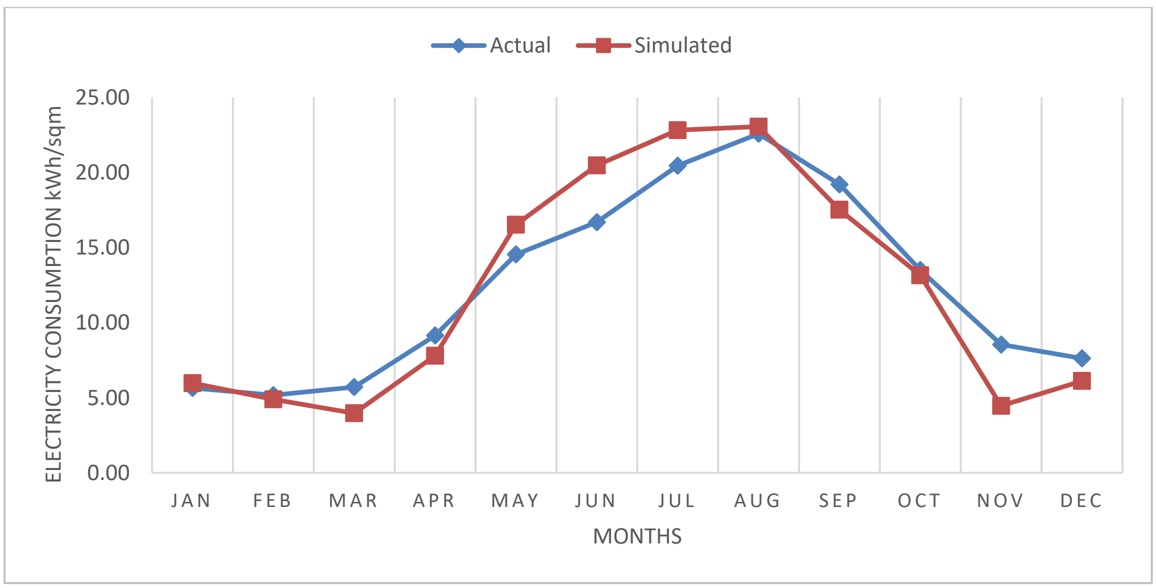


Figure 22: Calibration of the Villa Case Study Energy Model

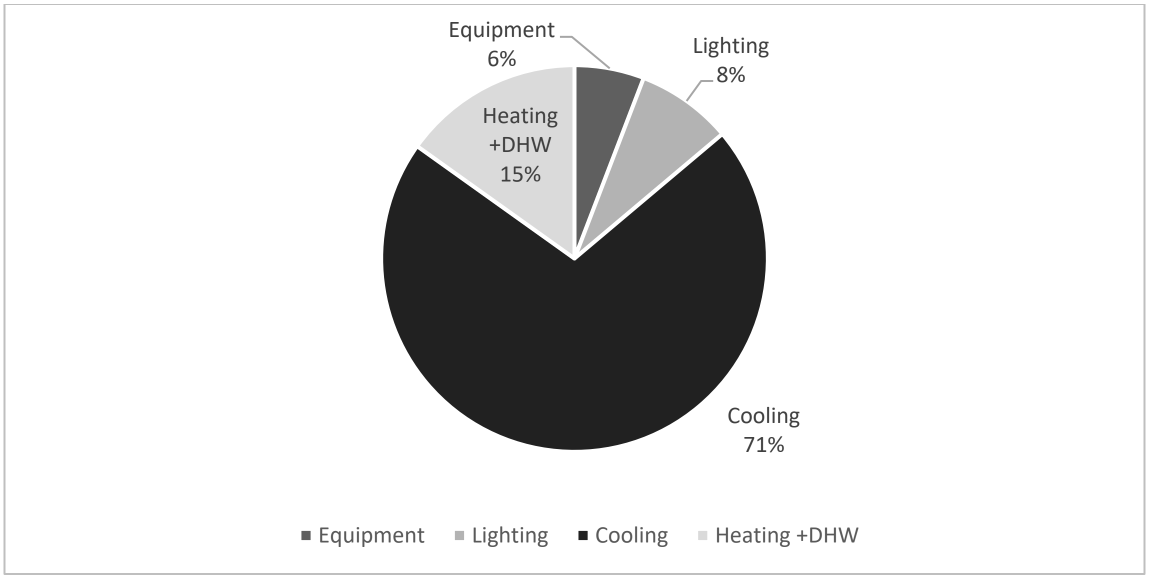


Figure 23: End-Use Energy Consumption of the Villa

The apartment building in reality is consuming 140,816.476 kWh of electricity per year which translates to an energy use index of 180.53 kWh/Sqm/Yr. Apartment buildings in the region typically have a EUI in the region of 196.5 kWh/Sqm/Yr (Alrashed & Asif, 2014). The simulated model has an Energy Use Index (EUI) of 172.41 kWh/Sqm/Yr, which is a difference of almost 4.5% from the actual consumption and is in the acceptable range (Fig.24). Regarding the end-use energy consumption, a similar trend to villas is visible where almost 70% of the energy consumption is required for cooling purposes which is an expected result (Fig.25).

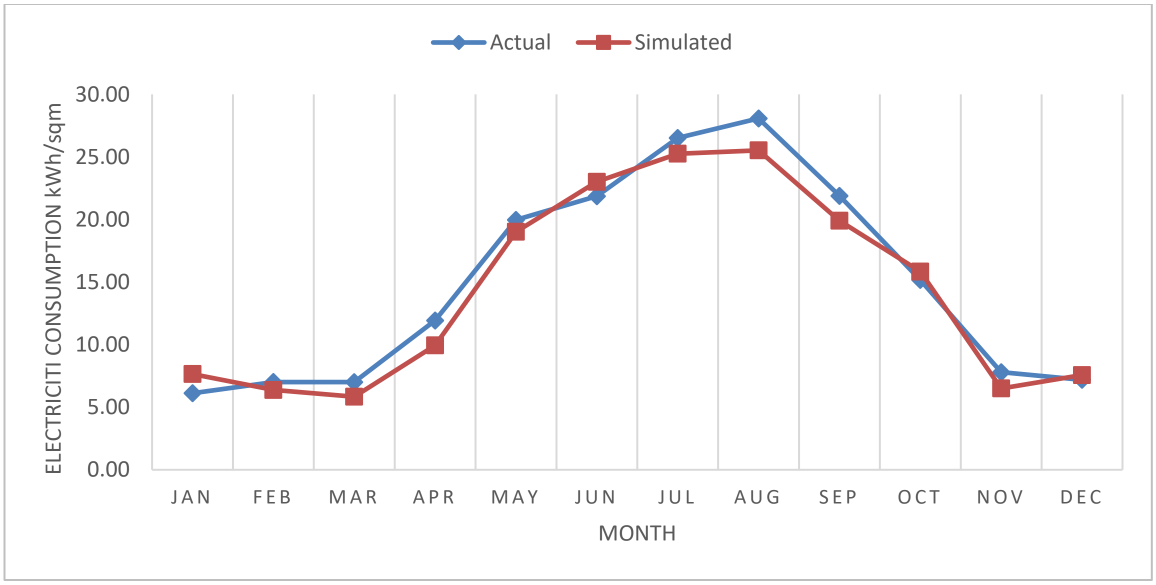


Figure 24: Calibration of the Apartment Case Study Energy Model

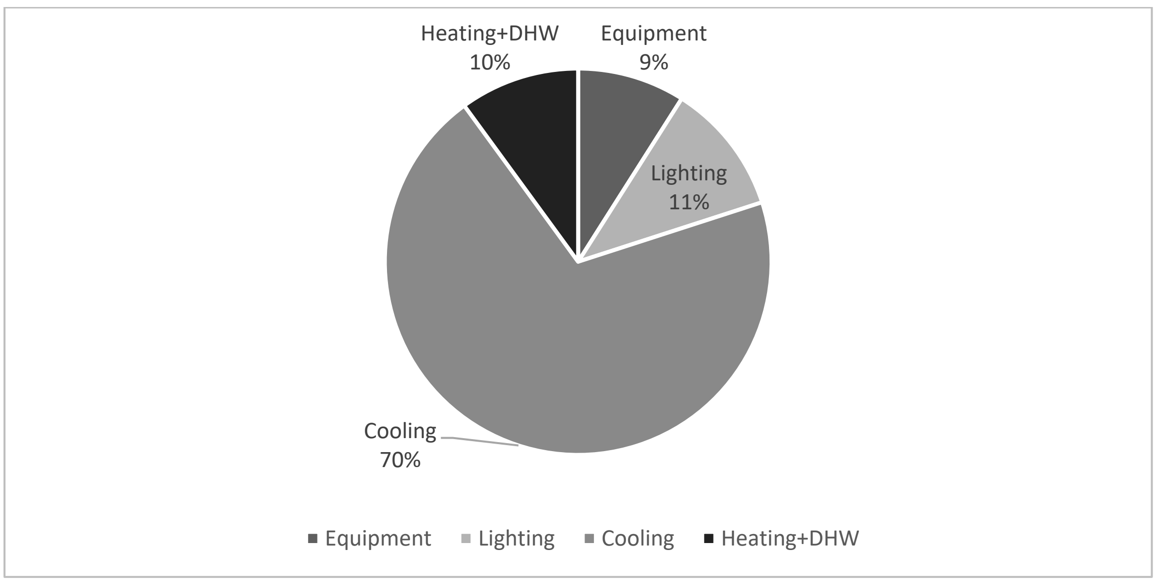


Figure 25: End-Use Energy Consumption of the Apartment Building

3.5 Rooftop PV Electricity Generation

The amount of energy generation achievable from a standard rooftop PV system in Eastern Province of Saudi Arabia is defined by (Dehwah, Asif, & Rahman, 2018) as 213 kWh/Sqm and 207 kWh/Sqm for villas and apartments respectively. They also defined the average amount of rooftop area available for installing rooftop PV panels in villas and apartments in the Eastern Region as 28% and 22% respectively. It was found that a total of 12,822.6 kWh and 11,840.4kWh of electricity can be generated by installed rooftop PV panels for the villa and apartment case study respectively. This is equivalent to 20.3% of the total yearly energy consumption of the villa case study and 9.3% of the apartment case study.

Table 4: Generated Electricity from Rooftop PV

Type	Rooftop Area (Sqm)	Usable Rooftop Area (Sqm)	Energy Yield/Sqm (kWh/Yr)	Total Generation (kWh/Yr)
Villa	215	60.2	213	12822.6
Apt.	260	57.2	207	11840.4

3.6 HVAC System Maintenance Practices Survey

Maintenance practices of HVAC system is generally overlooked and not paid attention to. However, literature and standards argue that timely preventive maintenance of the system will lead to prolonging the life of the system and save energy as well as prevent from unnecessary economic investment. (Suttel, 2006) in his report indicates that maintenance of HVAC system can be compared to the maintenance of a car, if oil is not changed and other engine parts are not checked and replaced the car will definitely stop working. Same is the case for HVAC systems. HVAC system filter, thermostat checking, cleaning dirt, lubricating moving parts, fan inspections, checking evaporative and condenser coils, and other aspects of HVAC systems should all be maintained and inspected in a timely manner. In fact, HVAC companies and codes such as ASHRAE have developed checklists indicating the time for scheduled maintenance for different HVAC aspects (ANSI/ASHRAE/ACCA, 2012)(ACCA, 2013). Adhering to these checklists and developing a preventive maintenance plan will result in energy savings in the long run.

HVAC system proper maintenance is a pre-requisite to the implementation of EEMs. As stated earlier, Saudi Arabia is a country where huge amounts of cooling is required to achieve thermal comfort level in buildings especially during the summer months. HVAC systems are a must in all residential buildings. To ensure proper operation of the HVAC system and to increase the life of the system, proper scheduled maintenance of the different components of the system should be conducted as recommended by standards such as ASHRAE and ACCA (ANSI/ASHRAE/ACCA, 2012) (ACCA, 2013). These standards have defined a checklist of maintenance recommendation on different HVAC components as well as have defined a schedule which should be followed. However, these standards may not be followed in residential buildings in Saudi Arabia.

In order to identify standard HVAC maintenance practices in residential buildings in Saudi Arabia, a questionnaire survey was conducted of homeowners. The broad objective of the survey is to benchmark existing maintenance practices with recommended practices from standards as well as HVAC manufacturers. The questions were divided into 2 main parts including:-

1. General questions: type of house, number of AC, type of AC, AC tonnage, set point temperatures, and age of AC system.
2. A checklist of AC components and their maintenance time: corrective, monthly, quarterly, half-yearly and yearly.

The results of the survey will identify the existing qualities of used HVAC systems in the houses through the general questions and will benchmark the existing maintenance practices through the second part.

3.7 Economic Analysis Method

Economic analysis was conducted to compare and justify the proposed retrofit levels and the case in which there is no change to the case studies. As described in section 2.7, there are several methods to perform life cycle costing. Two methods were chosen to perform the economic analysis. At first, Compound Payback Period was calculated for each of the proposed retrofit levels. CPP is a simple way of calculating the time it will take to return on the investments made. It is more effective than the Simple Payback Period (SPP) as it considers the time value of money. It is calculated by adding the yearly discounted cash flows until the cash flow is positive.

However, justifying the retrofit levels based on CPP will not be accurate as CPP only considers the initial investment and over the life time of the building additional costs might be present such as the maintenance and operation costs. Hence, Net Present Value (NPV) was selected to perform the economic analysis and compare between the three retrofit levels. The NPV can be calculated by the summation of all the profits and losses within a study period as indicated in equation 1. Cash flow diagrams of the study period can be developed as in figure 26.

$$\mathrm{NPV} = \sum_{y-1}^{y} \frac{Cy}{(1+r)^{y}} - C_0 \qquad (1)$$

Where:-
Cy is the yearly net cash flow
Co is the initial investment
Y is the time period
R is the interest rate

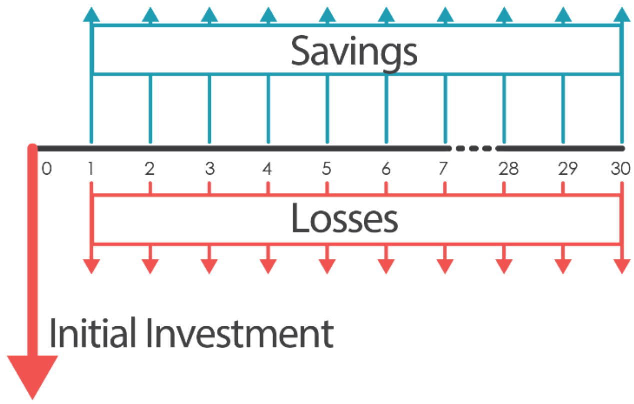


Figure 26: Example of a Cash Flow Diagram for NPV

The NPV was calculated for four scenarios, the existing case and the three proposed retrofit levels for each of the two case studies. The sum of all the cash flows at the present value is called the NPV which if positive or greater than the existing case indicates it is worth it to spend. In this case, the NPV of all the four scenarios will also be compared to find which scenario has the highest NPV indicating if it is worth it to invest in retrofitting at all or not, and if it is worth it which level of retrofit yields the best results.

The cost data was compiled for all the investments including electricity bills and initial investment for each of the proposed EEM. Electricity bills are calculated using the latest electricity tariffs provided by the Saudi electricity company for residential buildings in Saudi Arabia (Table 5).

Table 5: Electricity Tariff in Saudi Arabia

<table>
<tr><th>Consumption Category (kWh)</th><th>Residential (Halalah/ kWh)</th><th>Commercial (Halalah/ kWh)</th><th>Agricultural & Charities (Halalah/ kWh)</th><th>Governmental (Halalah/ kWh)</th><th>Industrial (Halalah/ kWh)</th></tr>
<tr><td>1-6,000</td><td>18</td><td>20</td><td>16</td><td rowspan="2">32</td><td rowspan="2">18</td></tr>
<tr><td>More than 6,000</td><td>30</td><td>30</td><td>20</td></tr>
</table>

3.8 Environmental Analysis Method

The environmental impact was measured by recording the amount of carbon dioxide production emitted by the existing case studies and compared with the reduction in emissions once each retrofit plan is implemented. DesignBuilder software calculates the carbon dioxide production based on the fuel breakdown and the factors which are published for the region. These factors are defined in the weather file as Kg of carbon dioxide produced per kWh fuel consumed. For the location, the fuel used was electricity and the factor defined was 0.685 Kg CO_2/ kWh. This means that every kWh of electricity that the case studies will use will result in the generation of 0.685 kg of CO_2. The CO_2 production from all the scenarios was computed to find out the amount of CO_2 reduction achieved through the different retrofit scenarios.

CHAPTER 4

Energy Efficiency Measures (EEMs)

In chapter 2, it was found that the best applicable EEMs in Saudi Arabia are the following eight:-

1. Increasing cooling set point temperature
2. Using energy efficient housing appliances
3. Replacing conventional lights with LED
4. Applying window shading
5. Improving glazing type
6. Improving air tightness
7. Using more efficient HVAC system
8. Adding envelope insulation

This section discusses the application and analyses the energy reduction possible through each of the above EEM on the two case studies/ The EEMs have been selected in accordance to literature review findings and various codes and standards wherever applicable. Different energy efficiency studies in the region including Saudi Arabia have utilized different energy codes to improve the energy efficiency standards of existing buildings. For example, International Energy Conservation Code (IECC) provides descriptive information on developing energy efficient building envelopes, mechanical, lighting and power systems. In the regional and local category, similar standards have been defined by the UAE based pearl energy rating system, Kuwait in collaboration with

American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) codes called ASHRAE 90.2-Kuwait as well as the local Saudi codes called SBC 601.

The SBC 601 is a comprehensive set of building energy codes which defines minimum performance levels for certain building features and requires energy modelling to assess whether building complies with the requirements. For a residential building in this climate with 8% window-wall ratio the codes require a maximum glazing u-value of 2.39 W/Sqm-K and a minimum u-value (m^2K/W) of 0.164 W/Sqm-K, 0.357 1 W/Sqm-K, and 0.303 1 W/Sqm-K for roof, exterior wall and floor respectively. However SBC 601 is an outdated set of codes developed in 2007 which needs to be updated and is hard to interpret, hence the UAE based pearl energy rating, Kuwait based ASHRAE 90.2 and IECC were also analysed to develop these.

Table 6 summarizes the existing characteristics of each EEM and the proposed ones. Further details on the proposed EEMs are discussed in sections 4.1 to 4.8. Furthermore, energy analysis is done of the application of each of the EEM on both of the case studies and the results are presented.

Table 6: Summary of the Proposed EEMs

No.	EEM	Existing	Proposed
1	Increasing cooling set point temp.	21◦C	24◦C
2	Using energy efficient appliances	Inefficient (4 W/Sqm)	Efficient (1.75 W/Sqm)
3	Replacing conventional lights with more efficient lights	Fluorescent (LPD = 5 W/Sqm)	LED (LPD = 2.5 W/Sqm)
4	Applying window shading	None	0.5m overhang
5	Improve glazing type	Single Clear U Value: 6.1 W/Sqm-K	Double Low-e (Argon Filled) U-Value: 1.5 W/Sqm-K
6	Improving air tightness	Loose Building 1.2 AC/h	Tight Building 0.5 AC/h
7	More efficient HVAC system	Window A/C, COP 1.5	Split Systems, COP: 3
8	Adding envelope insulation	None Wall U-Value: 2.23 W/Sqm-K Roof U-Value: 1.934 W/Sqm-K	R-30 Board Insulation Wall U-Value: 0.544 W/Sqm-K Roof U-Value: 0.525 W/Sqm-K

4.1 Increasing Cooling Set Point Temperature

In the previous section, it was highlighted that the cooling set point temperature is set very low in homes in Saudi Arabia. In a country with such high cooling demands increasing the set point temperature by each degree will result in energy consumption reduction in the home. In section 2.4.2, it was highlighted in literature that increasing the cooling set point temperature has resulted in significant energy savings for various building types in Saudi Arabia. It is also recommended by the Saudi Energy Efficiency Centre (SEEC) to set cooling temperatures at 24◦C. Hence, a cooling set point temperature of 24◦C was set for the two case studies and energy simulation was conducted.

Setting the cooling temperature to 24◦C has resulted in reduced energy consumption for both cases (Fig.27). Yearly energy consumption in the villa was reduced by 4.78% in the villa and in the apartment by 2.56%. Therefore, increasing the set point temperature is another zero cost EEM that can be immediately practiced by homeowners in the region.

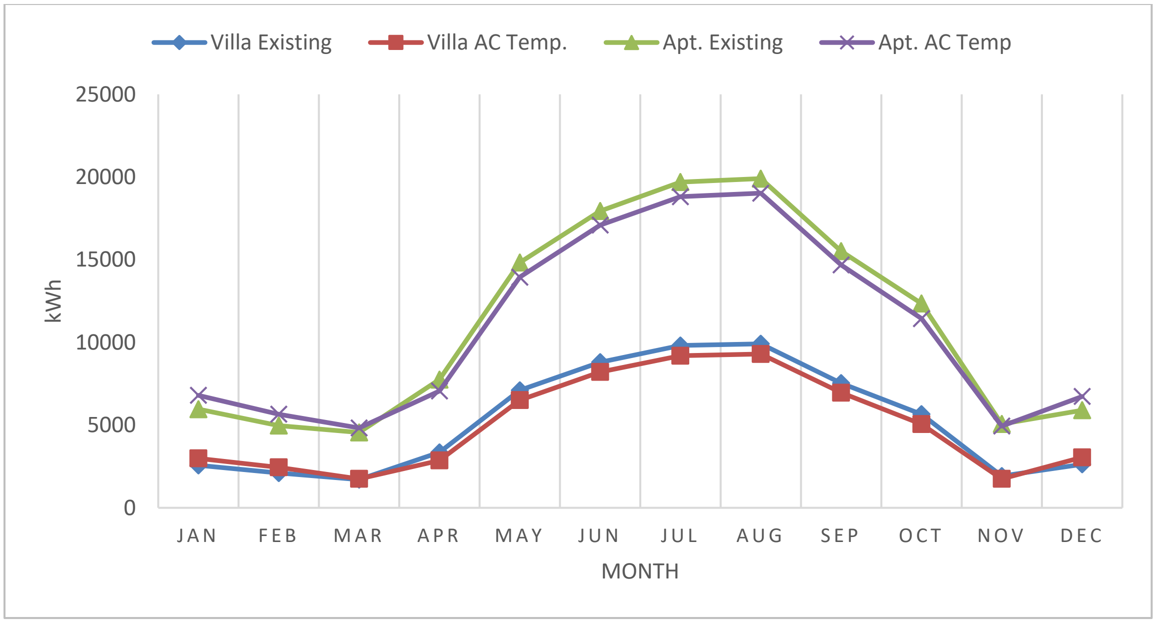


Figure 27: Energy Consumption Reduction-Cooling Temperature Set at 24◦C

4.2 Using Energy Efficient Housing Appliances

Home electric appliances such as the fridge, electric stove, microwave, TV, computers, iron etc. all consume energy in homes. In Saudi Arabia, it is only recently that energy efficient appliances are mandated by SEEC. Energy efficient appliances are expensive and homeowners who are not aware of energy efficiency usually select the cheaper options which are not as efficient. In the longer run though, the energy efficient appliances will save more as they will consume less energy. The IECC also recommends using appliances which are labelled by the energy star. Saudi Arabia also has a similar rating system as energy star developed by SASO which rates the appliances energy efficiency by stars.

In this study, all the inefficient appliances were replaced with class A level appliances in the two case studies. The inefficient or existing appliances were specified an average consumption rate of 4 W/Sqm in the case studies while after replacing them with class A appliances a consumption rate of 1.75 W/Sqm was achieved. The results show minimal energy consumption reduction in both cases with 1.50% and 2.23% reduction in the villa and apartment respectively (Fig.28).

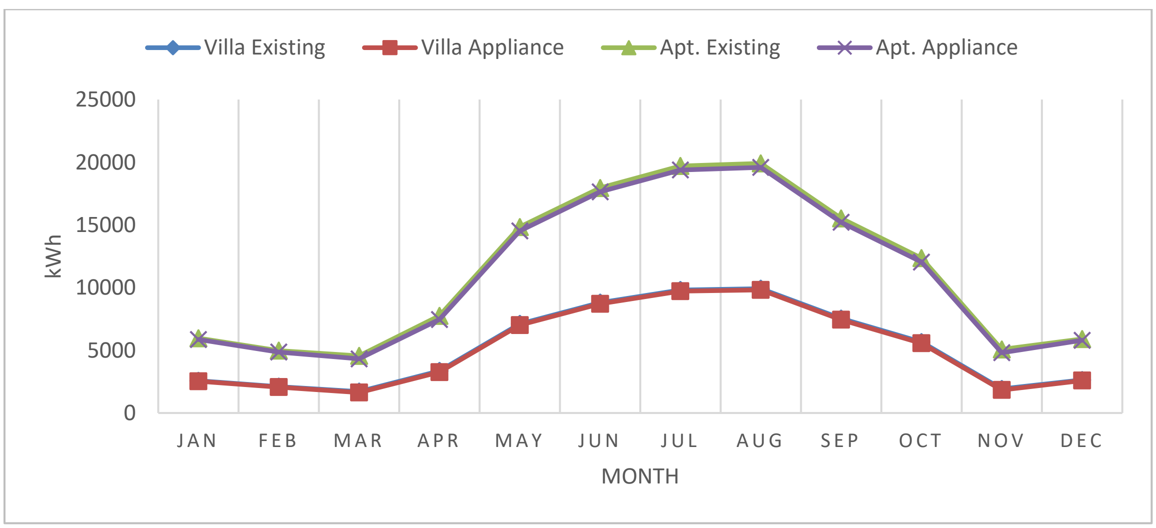


Figure 28: Energy Consumption Reduction - Efficient Appliances

4.3 Replacing Conventional Lights with LED

Existing buildings in Saudi Arabia are mostly depending on fluorescent tubes and in some extreme cases even incandescent lamps until now for lighting. LED lights have recently become popular in the market as their prices have started to drop. However, LED lights are still more expensive than fluorescent lights but in the long run will lead to savings due to the reduced energy consumption.

All the lights in the apartment and villa case studies were replaced with LED and the energy consumption reduction was measured. The existing lights have a Lighting Power Density (LPD) of 5 W/Sqm and the proposed LED have a LPD of 2.5 W/Sqm. The results indicate a very slight reduction in energy consumption of the villa by less than 1% and a slightly higher reduction in the apartment building of 4.7% (Fig. 29). This can be due to the fact that the apartment building has a higher number of lights and end use energy consumption by lights than the villa.

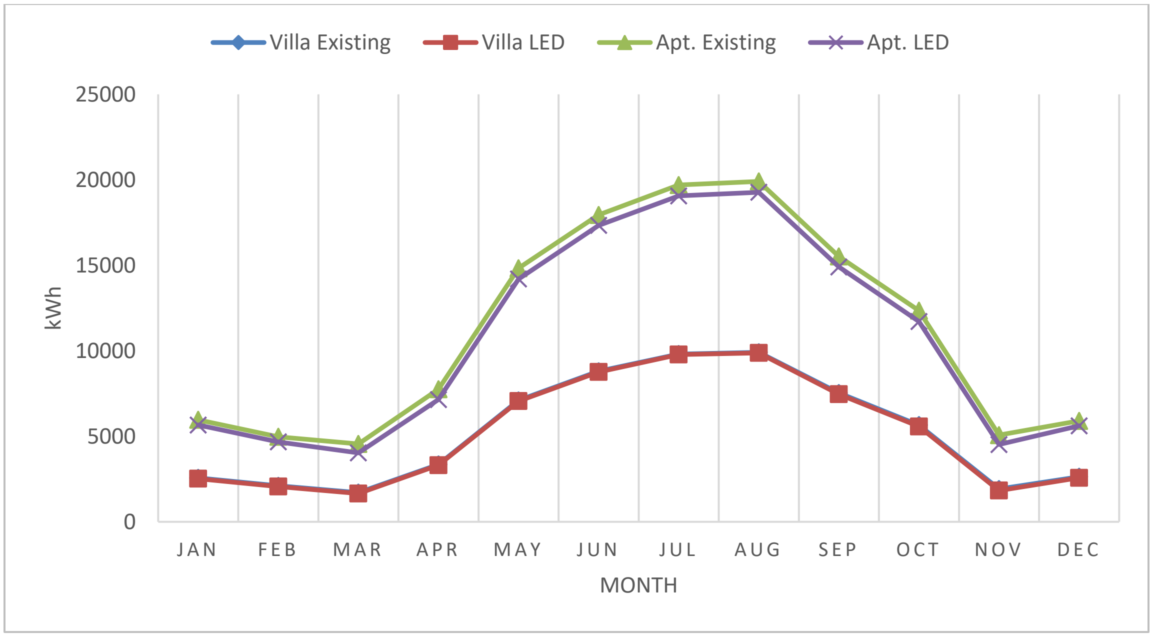


Figure 29: Energy Consumption Reduction - LED

4.4 Applying Window Shading

Shading devices above the windows will reduce the energy consumption in homes by blocking radiation to enter the building and thus reduce the SHGC. Currently, no shading device are installed as shading windows is seldom used in design in Saudi Arabia. Based on literature, a 0.5 m overhang shading device (Fig.30) was designed above all the windows of the two case studies.

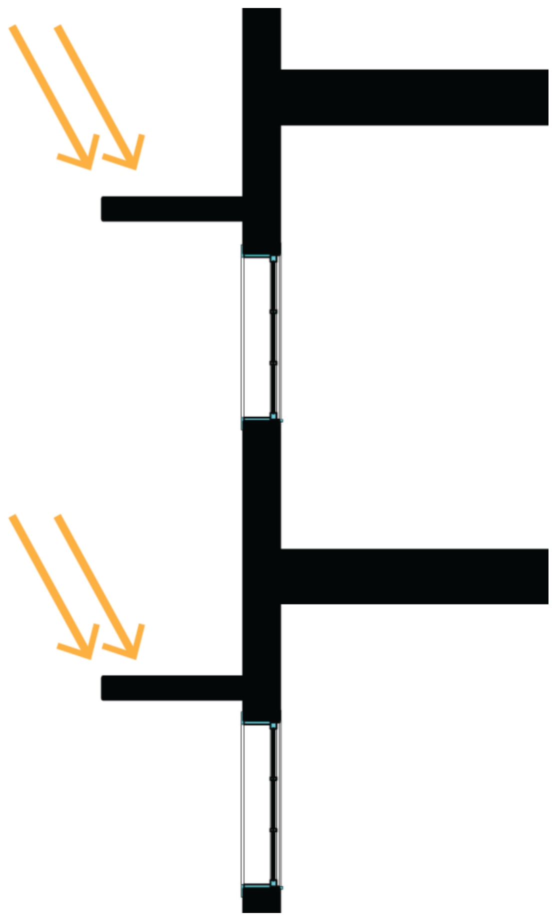


Figure 30: Shading Device Design for the Villa

The designed shading devices resulted in minimal yearly energy reduction for both the case studies. For the villa case study a reduction of 1.95% was achieved while for the apartment case study it was reduced by 1.50% (Fig.31). Thus applying shading devices can be considered as a low impact EEM.

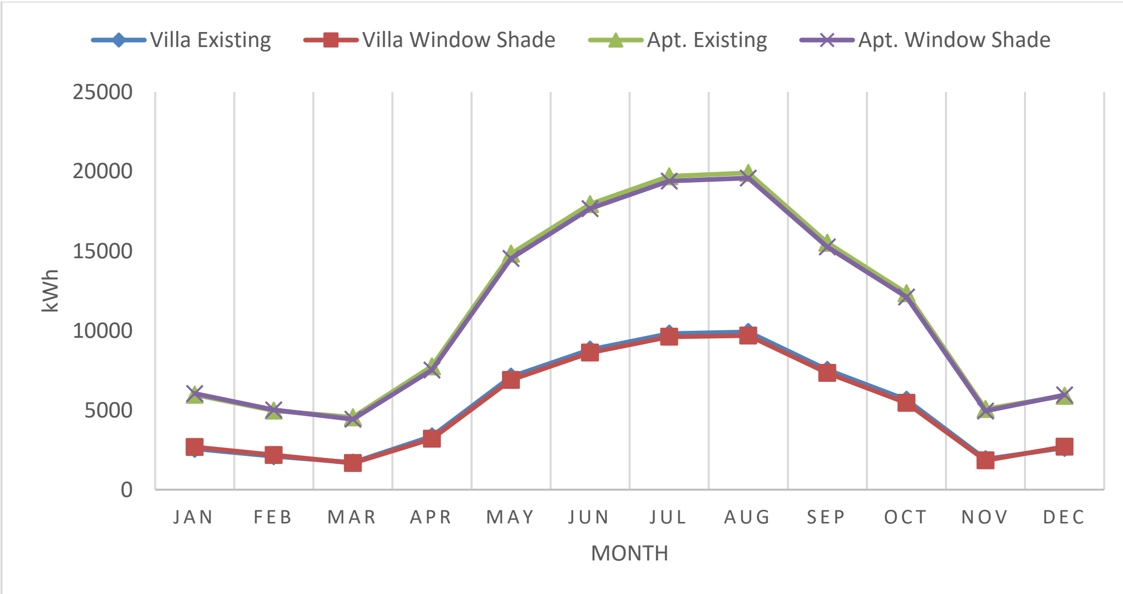


Figure 31: Energy Consumption Reduction – Window Shading Device

4.5 Improving Glazing Type

The glazing type can immensely determine the overall energy consumption of homes as it determines the amount of direct solar heat gain entering into the building. A window type with a high u-value will allow more solar heat gain to enter than the window with a lower u-value. In Saudi Arabia, the typical glazing type is single glazing as it has a cheaper initial cost than the double glazing. However, double glazing has a significantly lower u-value than the single glazing window. The recommended maximum u-value by different standards is as follows:-

- 2.39 W/Sqm-K – SBC 601
- 2.27 W/Sqm-K – IECC
- 2.67 W/Sqm-K – ASHRAE 90.2 Kuwait
- 2.00 W/Sqm-K – Pearl System Dubai

In accordance with the standards, a low-e argon filled double glazing with a u-value of 1.5 W/Sqm-K was proposed for both the case studies. All the glazing type of the all the windows were changed to the proposed type in Designbuilder and simulation was conducted. The results indicate a reduction in the yearly energy consumption of 3.73% in the villa case study and 4.26% in the apartment case study (Fig.32). The energy consumption reduction is possible for the specified w-w ratio for the two case studies.

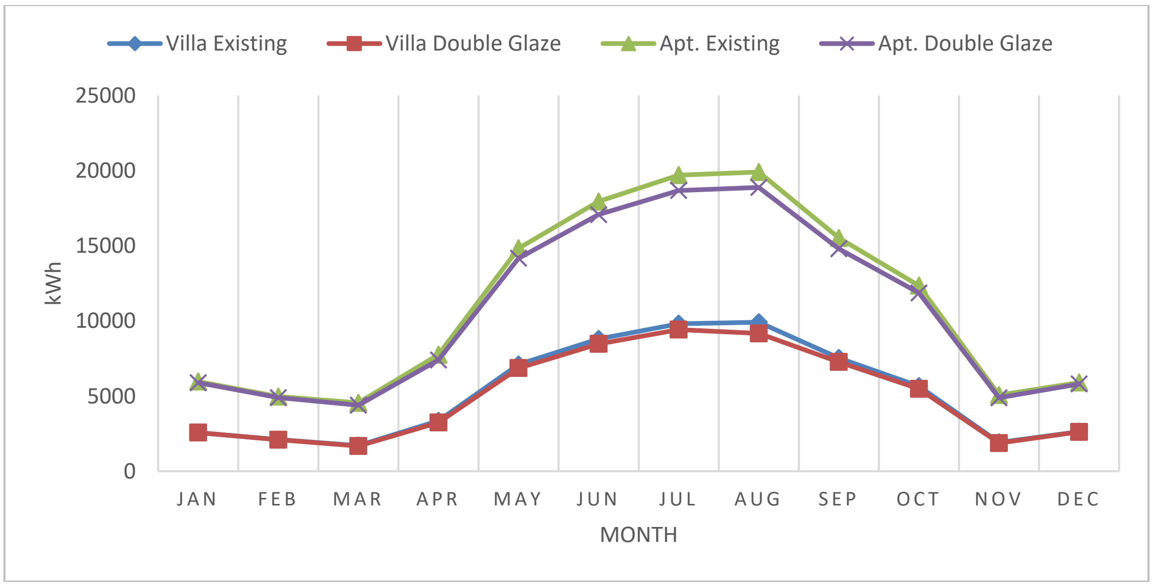


Figure 32: Energy Consumption Reduction - Double Glazing

4.6 Improving Air Tightness

The air tightness of the building affects the air infiltration rate (ac/h). The air infiltration rate determines the amount of outside air that seeps in through leakages in the building. These leakages might be present in the windows, doors and other opening in the building which are not properly sealed due to poor construction techniques. In Saudi Arabia, air tightness has a high impact on the energy consumption of the building as a lose building will allow outside hot air to seep in and thus the HVAC system has to cool more to achieve desire temperature. Therefore, the HVAC system will consume more electricity.

In Saudi Arabia, the construction technique is generally regarded as poor and the resulting buildings are not tight. The existing case studies considered as loose buildings have an infiltration rate of 1.2 ac/h and after sealing the windows and other openings the case studies are considered as medium tight buildings with an infiltration rate of 0.5 ac/h.

The results indicate that energy consumption of both case studies is highly reduced when the air infiltration rate is reduced. In the villa the consumption is reduced by 8.1% and in the apartment by 10.1% (Fig.33). Hence, air infiltration is considered as a medium impact EEM for the retrofit plan.

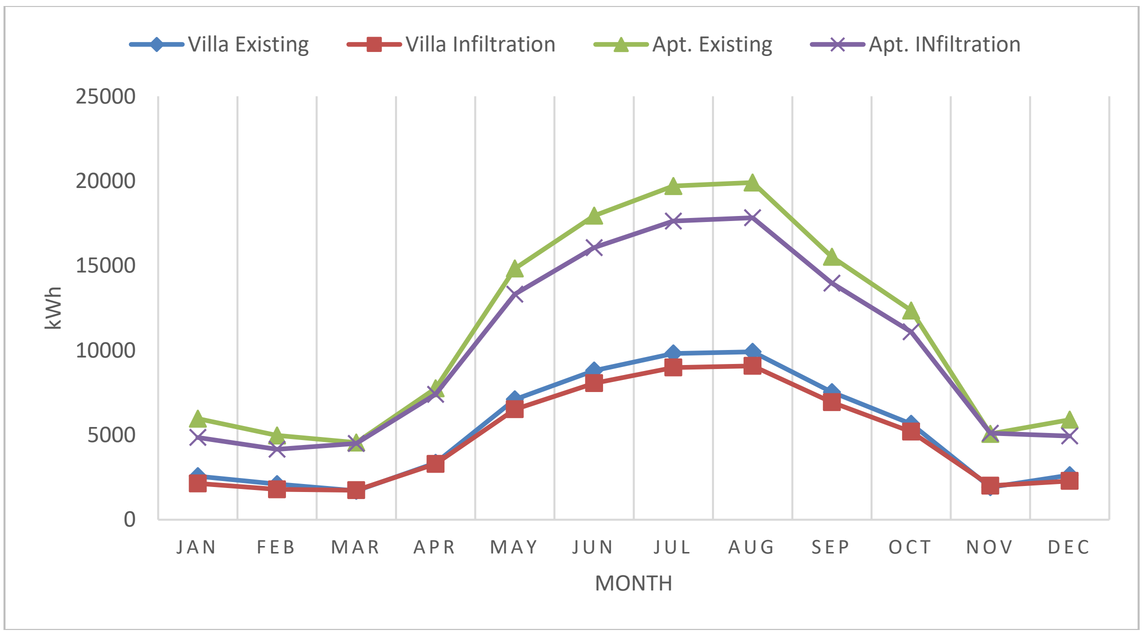


Figure 33: Energy Consumption Reduction – Reducing Air Infiltration

4.7 Using More Efficient HVAC System

Saudi Arabia is a country with huge cooling demands especially during the summer months and, as stated in previous sections, majority of the energy consumed is for cooling.

Therefore, the efficiency of the HVAC system is the most key determinant of the amount of electricity consumed in the residential buildings. Currently, as portrayed in the survey results in section 4.1, a lot of the homes have HVAC systems installed before 10 years and at that time energy efficiency was not mandated. Hence, as a result residents have installed the cheapest option and inefficient HVAC systems, as the case in the case studies. The Coefficient of Performance (COP) of the existing HVAC systems is 1.5 which is low. Standards have recommended higher value COP of HVAC systems in the region such as the two following standards which have defined the minimum COP levels as:-

- COP 2.12 - ASHRAE 90.2 Kuwait
- COP 3.28 - Pearl Rating System UAE

Similar standards have also been mandated by SEEC in Saudi Arabia. Hence, for the two case studies HVAC system of COP 3.5 was defined in Designbuilder software. The results indicate the maximum amount of reduction among all of the EEMs. For the villa the yearly energy consumption was reduced by 33.8% and in the apartment building it was reduced by 37.8 % (Fig.34).

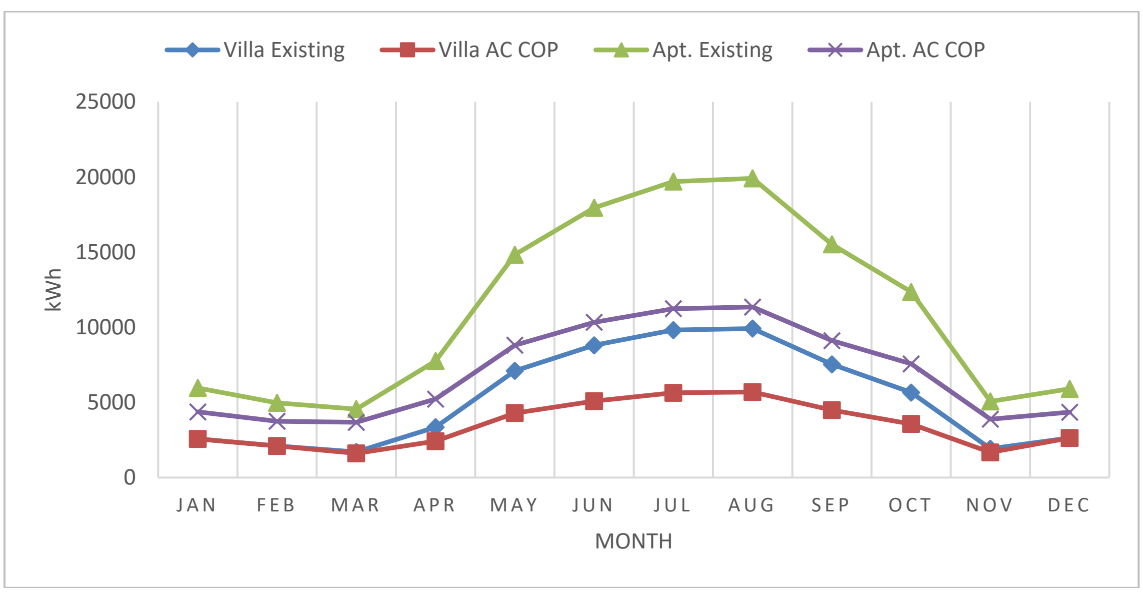


Figure 34: Energy Consumption Reduction - Higher AC COP

4.8 Adding Envelope Insulation

Existing homes built before thermal insulation was mandated by codes are having no thermal insulation in Saudi Arabia. Thermal insulation reduces the amount of heat gain through the envelopes. Having no thermal insulation in the walls and roofs results in huge amounts of excess energy consumption in the homes. Regional standards have defined the maximum u-values for wall and roofs as:-

- Wall: 0.453 W/Sqm-K , Roof: 0.273 W/Sqm-K - ASHRAE 90.2 Kuwait
- Wall: 0.30 W/Sqm-K , Roof: 0.20 W/Sqm-K - Pearl Rating System UAE

In the case study the existing wall and roof section was modified as seen in table 7. The results indicate a reduction in yearly energy consumption reduction of 18.9% in villa and 18.7% in the apartment building (Fig. 35).

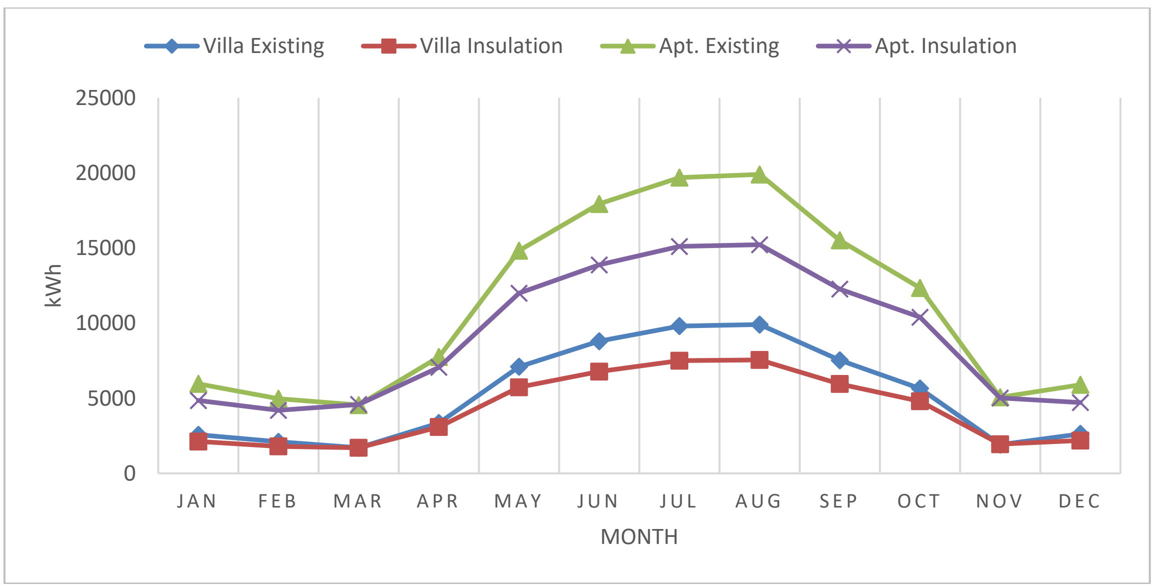
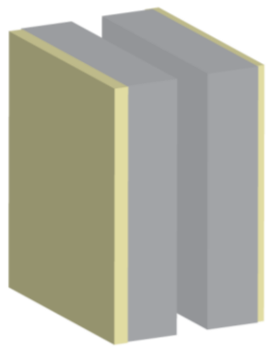
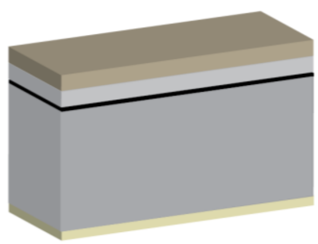
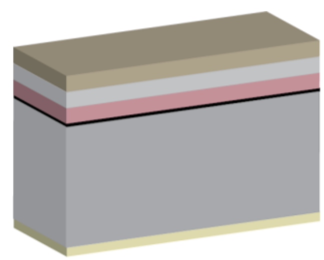


Figure 35: Energy Consumption Reduction - Envelope Insulation

Table 7: Existing and Proposed Envelope Details

Existing Wall		Insulated Wall	
25mm stucco,75mm concrete block,50mm Air Gap,75mm concrete block,25mm stucco U-value: 2.23 W/Sqm-K		25mm stucco,75mm concrete block,50mm R-30 board insulation,75mm concrete block,25mm stucco U-Value: 0.544 W/Sqm-K	
Existing Roof		Insulated Roof	
25mm terrazzo,25mm mortar,5mm bitumen layer,150mm cast concrete,200mm concrete block,15mm gypsum U-value: 1.934 W/Sqm-K		25mm terrazzo,25mm mortar,5mm bitumen layer, 50mm R-30 board insulation , 150mm cast concrete,200mm concrete block,15mm gypsum U-value: 0.525 W/Sqm-K	

CHAPTER 5

RESULTS AND DISCUSSIONS

In this chapter, the main results of the research are presented. So far in the thesis, case studies of a villa and apartment building have been presented and BIM and BEM models of the case studies are developed. Furthermore, EEMs were identified and implemented on the two case studies and it has been proved that implementing the EEMs will result in energy consumption reduction. This chapter will now present the results of the HVAC maintenance practices survey, energy, economic and environmental analysis and present an applicable retrofit plan.

5.1 HVAC System Maintenance Practices Survey Results

A total of 73 responses were obtained through an online survey. Majority of the survey respondents are living in apartments with 52% in apartments, 34% in villa, 10% in duplex, and the remaining in other types of residences. An average number of 3.5, 4.4, and 6.3 people are recorded as living in the apartment, duplex and villa respectively. The most type of HVAC system used is the split system with 58.5% using split, 45.1% using window and the rest have central HVAC installed.

Regarding the HVAC system condition, average age of the systems are 5.5, 7.2 and 10.25 years old in apartments, duplexes and villas respectively. This indicates that the HVAC systems are relatively older in villas. One possible reason could be that in villas a higher number of central systems are recorded and these are hard to replace over the years hence some of the HVAC system were recorded being more than 20 years old in villas. Having an HVAC system this old surely means that the system is inefficient if not maintained in the recommended way. The average tonnage of the HVAC systems in all the houses is recorded as being around 1.8 tons which is reasonable considering the size of the rooms in residential buildings.

The cooling and heating set point temperatures contribute to the amount of energy consumed in by the HVAC system. One of the major issues in Saudi buildings in overcooling of spaces as set point temperature are set very low. The survey found that for cooling an average temperature of 20◦C is set in the houses and for heating an average temperature of 23.5◦C is set. This shows that the cooling set point temperature is very low as optimum indoor temperature is at 24◦C, but this is also a very subjective issue as the cooling set point temperature depends on personnel thermal comfort in each house. However, residents should adapt and increase the cooling set point temperature to take into account the energy consumption as well.

The second part of the survey was a checklist to identify and benchmark the maintenance practices in the houses. A web diagram was developed (Fig.36) to compare the recommended schedule of maintenance and inspection of the various components and the practiced schedule. It is clear that the existing practice is clearly not following the recommended maintenance regime and inspection of the majority of the components is conducted as a corrective measure only. For example, it is recommended to replace the air filters every quarter as dust and dirt will accumulate on them and impact the efficiency of the system, however, in Saudi homes the replacement is done only for corrective measure when air filter is completely blocked. This means that there is a certain period of time in which the HVAC system is working inefficiently as air filter is not replaced in recommended time. Similarly, the efficiency of the HVAC system is reduced when all the other components are not inspected and maintained as per recommendations.

Developing and implementing a proper maintenance schedule for the HVAC systems in homes is one of the pre-retrofit measure that can be implemented in homes. The proper HVAC system maintenance is recommended to be implemented in all cases as a measure which will result in increasing the efficiency of the HVAC system.

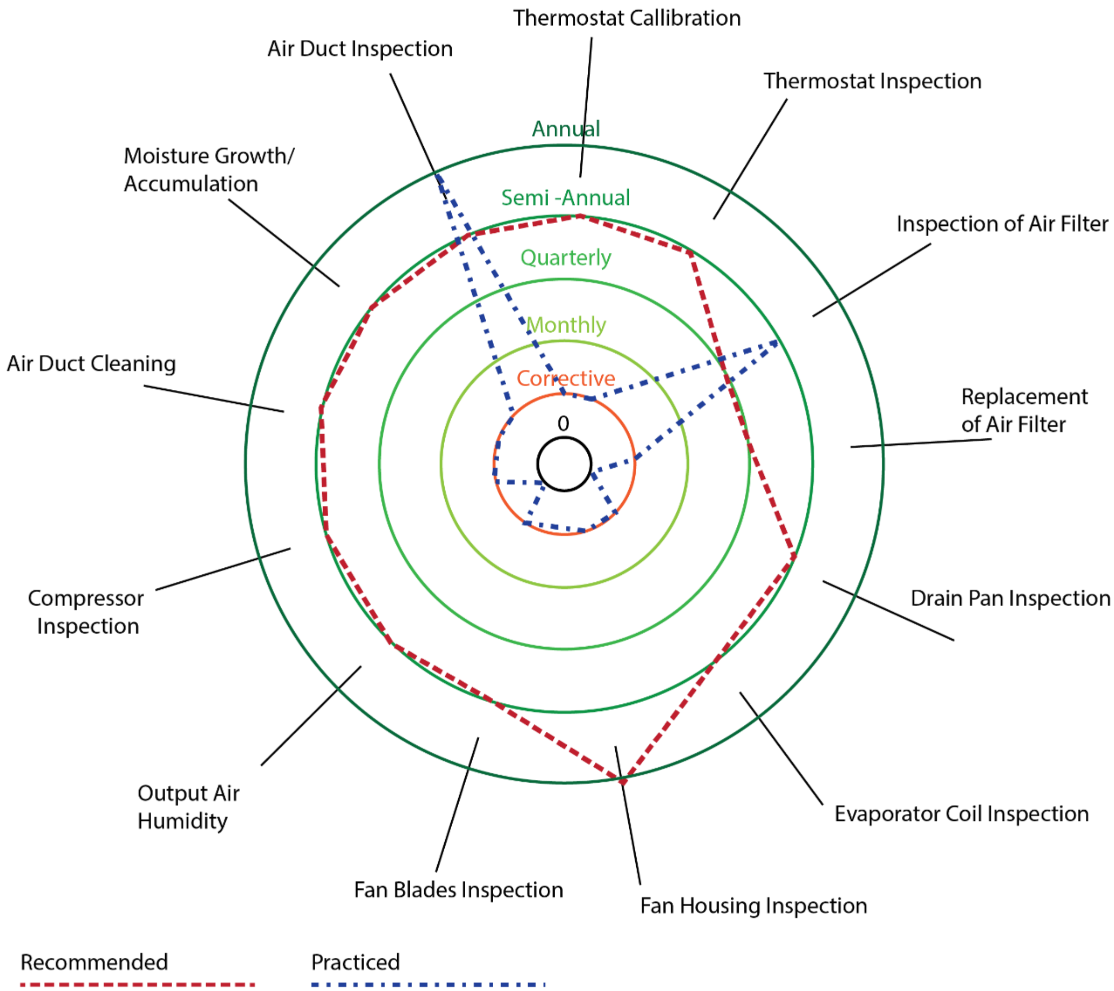


Figure 36: Web Diagram of Recommended Maintenance Schedule and Practiced Schedule in Saudi Homes

5.2 Energy Analysis

Implementation of the EEMs have resulted in energy consumption reduction compared to the existing buildings for both the case studies. For the villa, a minimum EUI of 97.14 kWh/Sqm/Yr was achieved through improving the AC COP (Fig.37). This is a reduction of 37.78% of energy as compared to the existing case. Other EEMs, have varying reduction with the least impact by the changing of lights to LED. In the apartment building a similar trend is seen, however some of the EEMs are behaving differently due to the building type. The AC COP is still the EEM with the highest impact on the energy consumption (Fig.38), however LED is not the EEM with the least impact and it reduced the consumption by 4.72% (Table 8). A possible reasoning for that is the higher number of lights present in apartment buildings.

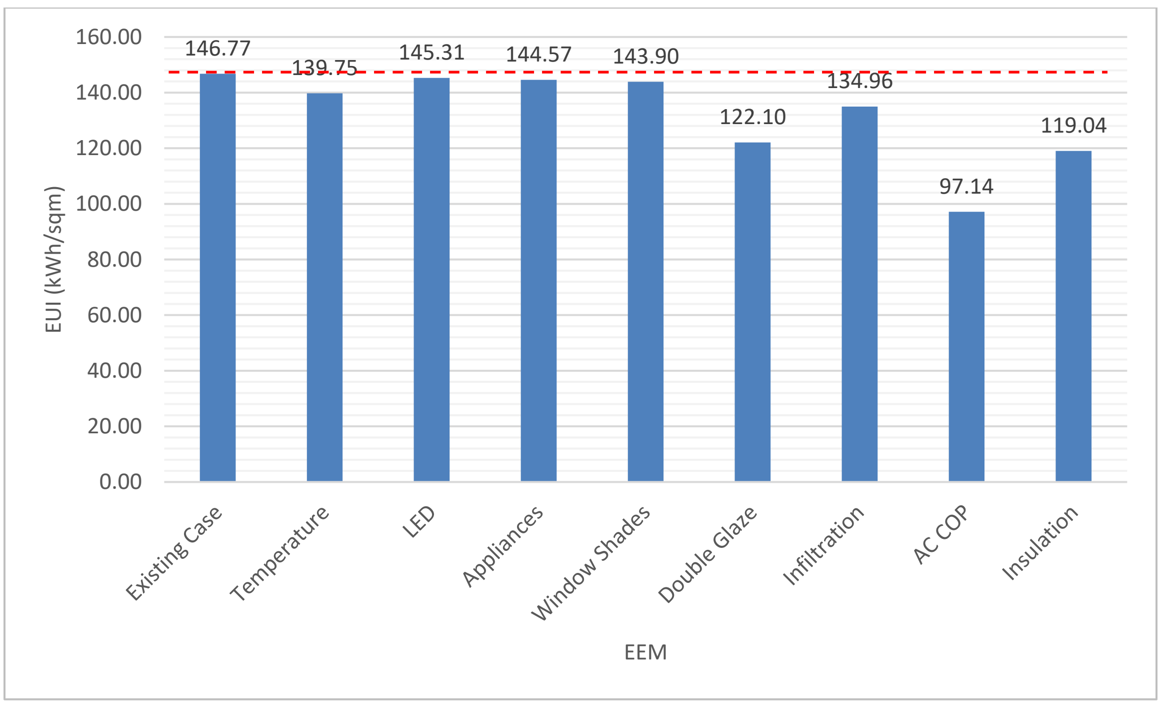


Figure 37: Energy Consumption Reduction by EEMs in Villa

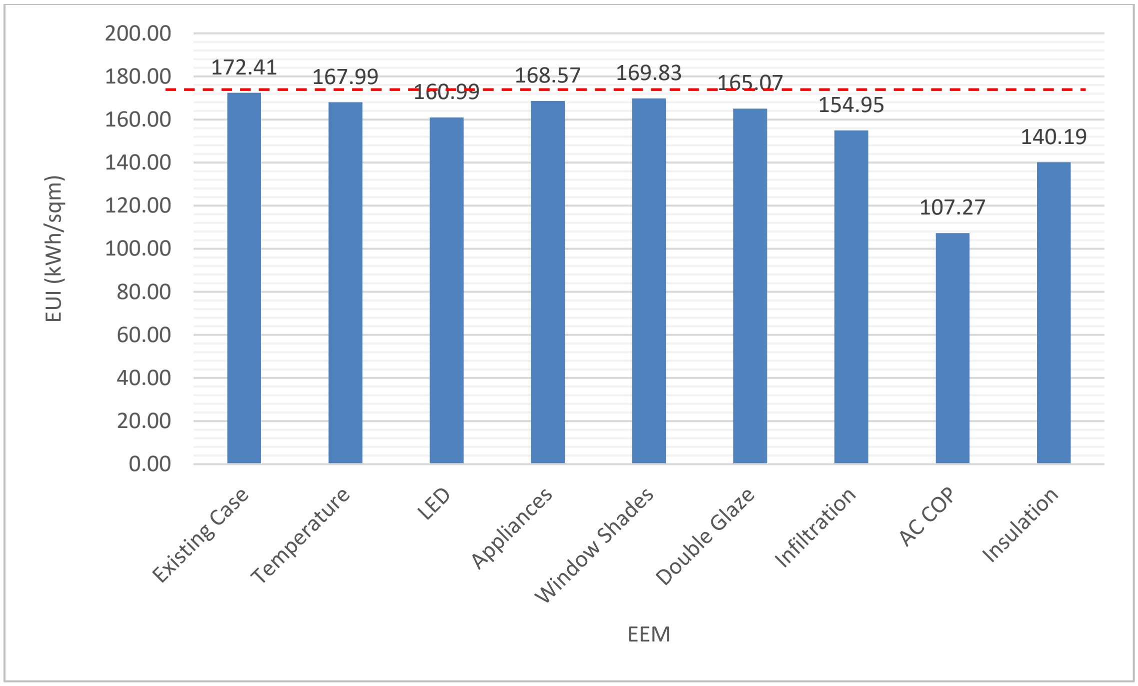


Figure 38: Energy Consumption Reduction by EEMs in Apartment Building

Table 8: Summary of Energy Analysis Results and Retrofit Level Proposal

No	EEM	Villa		Apt		Energy Impact
		EUI (kWh/Sqm/Yr)	Energy Reduced (%)	EUI (kWh/Sqm/Yr)	Energy Reduced (%)	
0	Existing Case	146.77	0	172.41	0.00	None
1	Temperature	139.75	4.78	167.99	2.56	Low
2	LED	145.31	1.00	164.27	4.72	Low
3	Appliances	144.57	1.50	168.57	2.23	Low
4	Window Shades	143.90	1.95	169.83	1.50	Low
5	Double Glaze	141.30	3.73	165.07	4.26	Low
6	Infiltration	134.96	8.05	154.95	10.13	Medium
7	AC COP	97.14	33.81	107.27	37.78	High
8	Insulation	119.04	18.89	140.19	18.69	Medium

5.3 Retrofit Plan Levels

Not all of the EEMs can be implemented at the same time due to practicality reasons. It may not be economically feasible for building owners or application of a certain EEM is not economically feasible at all. Therefore, the EEMs were divided into three levels to form a retrofit implementation plan. The EEMs were divided based on the cost of implementing each EEM and are as follows:-

1. Level 1: Low Cost Measures
2. Level 2: Medium Cost Measures
3. Level 3: High Cost Measures

The following section explains the initial cost data for each of the EEM for both the case studies.

5.3.1 Initial Costs of Implementing each EEM

Next, the capital cost of all the EEMs was calculated. Construction material and labour cost was found from (AECOM, 2018) (Concrete Construction Magazine, n.d.). Furthermore, all the other costs were derived from local knowledge and relevant sources in the local construction industry. All the cost related data for each of the EEM is presented in tables 9 to 15. The first two EEMs which are proper maintenance of HVAC system and increasing cooling set point temperature are zero investment measures, hence no cost data is presented for them.

Table 9: Capital Costs for LED

Case Study	**Cost/Lamp (SR)**	**Total Lamps**	**Total Cost (SR)**
Villa	10	47	470
Apartment		126	1260

Table 10: Capital Costs for Appliances

Case Study	Appliance	Unit Cost (SR)	Quantity	Total Cost (SR)
Villa	Fridge	3,000	1	3,000
	Electric Stove	2,500	1	2,500
	Microwave	800	1	800
	Washing Machine	4,000	1	4,000
	Clothes Dryer	1,500	1	1,500
	TV	2,000	1	2,000
	Total			**13,800**
Apartment Building	Fridge	3,000	6	18,000
	Electric Stove	2,500	6	15,000
	Microwave	800	6	4,800
	Washing Machine	4,000	6	24,000
	Clothes Dryer	1,500	6	9,000
	TV	2,000	6	12,000
	Total			**82,800**

Table 11: Capital Costs for Window Shading

Case Study	Item	Unit Cost (SR)	Quantity	Total Cost (SR)
Villa	Material	15/ m^3	2.72	40.8
	Labour	25.5/hr	16 hrs	408
	Total			**448.8**
Apartment Building	Material	15/ m^3	4.32	64.8
	Labour	25.5/hr	48 hrs	1,224
	Total			**1,228**

Table 12: Capital Costs for Double Glazing

Case Study	Unit Cost (SR)	Quantity	Total Cost
Villa	500 (All costs/window)	17	8,500
Apartment Building	500 (All costs/window)	36	18,000

Table 13: Capital Costs for Infiltration

Case Study	Item	Unit Cost	Quantity	Total Cost (SR)
Villa	Material	60 SR/Window	17 windows	1,020
	Labour	27.75/hr	8 hrs	222
	Total			**1,242**
Apartment Building	Material	60 SR/Window	36 windows	2,160
	Labour	27.75/hr	8 hrs	222
	Total			**2,382**

Table 14: Capital Costs for HVAC System

Case Study	Item	Unit Cost (SR)	Quantity	Total Cost (SR)
Villa	System	3,500	14	49,000
	Labour+Transport	500	1	500
	Total			**49,500**
Apartment Building	System	3,500	48	168,000
	Labour+Transport	1,000	1	1,000
	Total			**169,000**

Table 15: Capital Costs for Insulation

Case Study	Item		Unit Cost (SR)	Quantity	Total Cost (SR)
Villa	Demolish	Material	15/ m³	423.16(m³)	6,347.4
		Labour	25.5/hr	24 (hrs)	612
	Build	Material	73/m³	423.16(m³)	30,890.68
		Labour	25.5/hr	1,800 (hrs)	45,900
	Total				**83,750.08**
Apartment Building	Demolish	Material	15/m³	739.2(m³)	11,088
		Labour	25.5/hr	48 (hrs)	1,224
	Build	Material	73/m³	739.2(m³)	53,961.6
		Labour	25.5/hr	3120 (hrs)	79,560
	Total				**145,833.60**

5.3.2 Categorization of EEMS into Levels

Based on the initial cost data, the EEMs are now categorized into the 3 retrofit levels as explained earlier (Table 16). Level 1 contains low cost EEMs which can be invested into easily. The EEMs in this level can also be defined as low energy impact and easily implementable EEMs including increasing the cooling set point temperature, and replacing existing lights with LED, applying window shading and sealing air leakages. Increasing cooling set point temperature is another zero investment EEM requiring just change of habits. LED can also easily be bought and implemented without much labour intensive work.

Level 2 contains all level 1 EEMs and in addition other medium cost EEMs which require some effort in implementation. The additional EEMs in the level include using double glazing, and buying new energy rated appliances. Implementation of the EEMs requires more investment in this level than level 1.

Level 3 contains all EEMs of level 1 and level 2 an in addition replacing HVAC systems and application of envelope insulation. These two EEMs are the most costly and have the highest impact on the energy consumption of the case studies and require the most effort in implementation. Skilled labour are needed to install new HVAC systems as well as to demolish and construct new envelope with insulation

Table 16: Categorization of the EEMs into Retrofit Levels Based on Cost

No.	EEM	Cost (SR)	Retrofit Level
Villa			
1	Cooling Set point	0	No or Low Cost
2	Window Shading	448.8	
3	LED	470	
4	Sealing Leakages	1,242	
5	Double Glazing	8,500	Medium Cost
6	Efficient Appliances	13,800	
7	HVAC Efficiency	49,500	High Cost
8	Insulation	83,750.08	
Apartment Building			
1	Cooling Set point	0	No or Low Cost
2	Window Shading	1,228	
3	LED	1,260	
4	Sealing Leakages	2,382	
5	Double Glazing	18,000	Medium Cost
6	Efficient Appliances	82,800	
7	HVAC Efficiency	169,000	High Cost
8	Insulation	145,833.60	

The energy consumption reduction achievable through each retrofit level needs to be computed again, hence each plan was implemented on the two case studies and energy simulation was conducted. The resulting energy consumption is summarised in figures 39 and 40.

Figure 39: Energy Consumption Reduction by each Retrofit Plan Level in Villa

Figure 40: Consumption Reduction by each Retrofit Plan Level in Apartment Building

The general trend indicates a reduction in energy consumption as the retrofit level is increased in both cases. In the villa, implementing the retrofit plan reduces annual energy consumption by 13.8%, 19.2% and 56.9% for each level 1, 2 and 3 respectively. The final EUI of the completely retrofitted villa is 63.25 kWh/Sqm/Yr. Similarly, for the apartment building the annual energy consumption is reduced by 22.8%, 28.9% and 58.5% for each level 1, 2 and 3 respectively. The final EUI of the retrofitted apartment building is 58.5 kWh/Sqm/Yr.

Energy analysis results have indicated that significant energy consumption reduction is achievable through the implementation of the retrofit plan. It is logical to say that a level 3 retrofit should be immediately selected and implemented as it will result in significant energy savings overall. However, it may not be economically feasible and the economic analysis may suggest otherwise. The next step is to conduct the economic analysis and evaluate the economic impact of each proposed retrofit levels.

5.4 Economic Analysis

This section presents the results of the economic analysis conducted. Initial cost of implementing each retrofit level was calculated through the data presented in section 5.3.1. Next, the electricity bills for each level was calculated. Finally, Simple Payback Period and NPV was calculated for the proposed retrofit levels.

5.4.1 Annual Electricity Bills

In order to conduct the economic analysis, all the related cost data was gathered including electricity bills for the existing and retrofitted scenarios, as well as capital costs of each of the retrofit level. The electricity bill pricing was done in accordance to the tariffs set by the SEC. The existing villa bill is calculated to be 20,140.3 SR annually and it is reduced to

10,556.49 SR, 9736.2 SR and 4896.1 SR after the implementation of level 1, 2 and 3 retrofit respectively (Table 17). The existing apartment building bill is 32,127.6 SR and it is reduced to 23,785.09 SR, 21,568.6 SR, and 10,314.5 SR after the implementation of level 1, 2 and 3 retrofit respectively (Table 18).

Table 17: Electricity Cost for Existing and Retrofitted Cases - Villa

	Existing		**Level 1**		**Level 2**		**Level 3**	
Month	kWh	Bill (SR)	kWh	Bill (SR)	kWh	Bill (SR)	kWh	Bill (SR)
Jan	2570.00	462.60	2672.94	481.13	2431.50	437.67	1629.70	293.35
Feb	2104.00	378.72	2196.73	395.41	1995.62	359.21	1404.09	252.74
Mar	1706.00	307.08	1601.59	288.29	1481.06	266.59	1371.20	246.82
Apr	3354.00	603.72	2742.66	493.68	2551.12	459.20	1866.64	336.00
May	7104.00	1411.20	5861.61	1055.09	5530.44	995.48	2761.51	497.07
Jun	8804.00	3721.20	7403.36	1501.01	6976.13	1372.84	3056.28	550.13
Jul	9813.00	4023.90	8316.19	1774.86	7833.00	1629.90	3379.03	608.23
Aug	9914.00	4054.20	8382.48	1794.74	7904.06	1651.22	3392.67	610.68
Sep	7534.00	3340.20	6255.79	1156.74	5915.95	1064.87	2801.04	504.19
Oct	5658.00	1018.44	4526.3	814.73	4269.13	768.44	2403.42	432.62
Nov	1918.00	345.24	1666.05	299.89	1535.13	276.32	1424.27	256.37
Dec	2632.00	473.76	2782.93	500.93	2524.95	454.49	1710.68	307.92
Total Year	**63111.0**	**20140.3**	**54408.63**	**10556.49**	**50948.1**	**9736.2**	**27200.5**	**4896.1**

Table 18: Electricity Cost for Existing and Retrofitted Cases - Apartment Building

	Existing		**Level 1**		**Level 2**		**Level 3**	
Month	kWh	Bill (SR)	kWh	Bill (SR)	kWh	Bill (SR)	kWh	Bill (SR)
Jan	5966.00	1073.88	4455.42	801.98	4270.50	768.69	3033.42	546.02
Feb	4973.39	895.21	3700.92	666.17	3533.69	636.06	2678.20	482.08
Mar	4555.10	819.92	3217.87	579.22	2938.46	528.92	2985.94	537.47
Apr	7753.62	1606.09	5653.47	1017.62	5096.35	917.34	3851.0	693.18
May	14832.75	3729.83	11401.47	2700.44	10492.3	2427.70	5746.8	1034.42
Jun	17947.22	4664.17	14202.81	3540.84	13062.13	3198.64	6436.46	1210.94
Jul	19698.36	5189.51	15697.27	3989.18	14400.94	3600.28	6908.87	1352.66
Aug	19907.18	5252.15	15870.79	4041.24	14579.31	3653.79	6973.50	1372.05
Sep	15519.45	3935.84	12146.99	2924.10	11180.57	2634.17	5841.36	1051.44
Oct	12352.62	2985.79	9244.8	2053.44	8509.06	1832.72	5125.84	922.65
Nov	5070.29	912.65	3647.67	656.58	3292.19	592.59	3128.94	563.21
Dec	5903.06	1062.55	4523.43	814.22	4320.39	777.67	3046.33	548.34
Total Year	**134479.0**	**32127.6**	**103762.9**	**23785.019**	**95675.9**	**21568.6**	**55756.6**	**10314.5**

5.4.2 Payback Period

The SPP was calculated to identify the time required to return on the investments for each EEM. Table 19 summarizes the calculated SPP for each EEM application individually in both of the case studies. Generally, the trend is similar for the EEMs in both the case studies except for the appliances and glazing. In the villa, investment in the low and medium impact EEMs will return on investment within 2 years. The two high impact EEMs including AC COP and envelope insulation will take 4 and 8 years respectively. In the apartment building however, the appliances capital cost is huge as new appliances will be needed for the six apartments, thus it results in a payback period of more than 100 years which is not feasible.

Table 19: SPP of each EEM

EEM	Annual Energy Consumption (kWh)	Annual Bill (SR)	Annual Savings (SR)	Initial Investment (SR)	Payback Period (Years)
Villa					
Cooling SP	60091.64	12038.13	8,102.17	-	-
Shading	61879	12596.58	7,543.72	448.8	0.06
LED	62482	12800.4	7,339.90	470	0.06
Infiltration	58032	11594.88	8,545.42	1,242	0.15
Glazing	60758	12279.84	7,860.46	8,500	1.08
Appliances	62166	12712.32	7,427.98	13,800	1.86
AC	41771	7518.78	12,621.52	49,500	3.92
Insulation	51189.2	9674.80	10,465.50	83,750.08	8.00
Apartment Building					
Cooling SP	131032.50	30977.98	1149.62	-	-
Shading	132467.85	31539.12	588.48	1228.00	2.09
LED	128129.17	30459.35	1668.25	1260.00	0.76
Infiltration	120858.23	28390.25	3737.35	2382.00	0.64
Glazing	128752.41	30480.74	1646.86	18000.00	10.93
Appliances	131485.43	31327.19	800.41	82800.00	103.45
AC	83668.44	17749.30	14378.30	169000.00	11.75
Insulation	109345.57	24957.72	7169.88	145833.60	20.34

Next, the Compound Payback Period (CPP) of the implementation of each of the retrofit level on the two case studies was calculated (Table 20). A level 1 retrofit comprising of low cost EEMs will return in less than a year for both case studies. A full level 3 retrofit for the villa will return in 11.71 years and 24.60 years for apartment building which is feasible for the villa but not for the apartment building considering the building life is 30 years.

Table 20: CPP of each Retrofit Implementation Plan Level

Scenario	**Annual Energy Consumption (kWh)**	**Annual Bill (SR)**	**Annual Savings (SR)**	**Initial Investment (SR)**	**Payback Period (Years)**
Villa					
Existing	63111	20,140.30	-	-	-
Level 1	54408.63	10556.5	9,583.81	2,161	0.23
Level 2	50948.09	9736.2	10,404.10	24,460.80	2.43
Level 3	27200.53	4,896.10	15,244.20	157,711	11.71
Apartment Building					
Existing	134479.04	32127.60	-	-	-
Level 1	116264.50	23785.02	8342.58	4870.00	0.60
Level 2	95675.90	21568.59	10559.01	105670.00	11.27
Level 3	55756.60	10314.46	21813.14	420503.60	24.60

5.4.3 Net Present Value (NPV)

The NPV was calculated for all the cases for both case studies. The following considerations were taken in the calculations:-

- The building life is considered to be 30 years.
- The service life of all electrical appliances, LED and HVAC systems is considered as 15 years.
- Maintenance cost of HVAC systems is considered based on annual scheduled maintenance contracts = 500 SR/year.

- Maintenance cost of appliances is not considered.
- Any over time degradation of energy efficiency is not considered.
- The interest rate in Saudi Arabia is taken as 2%.

The resulting cash flows can be seen in figure 41 for the villa and figure 42 for the apartment building. The present value of all the annual costs seen in the cash flows was calculated for both the case studies. The NPV of all the scenarios is summarized in Table 21. All the calculated NPVs are negative as all of them are implying losses. The NPV with the least loss is the most profitable scenario.

For both the cases, we see that the NPV of the existing cases is the least profitable one, implying that implementation of any retrofit level is economically viable than the existing scenario. For the villa, the NPV of the existing villa is -1281670.34 SR and for the apartment building it is -3982387.90 SR. Contrary to what was found in the energy analysis, the NPV analysis indicates that the level 1 retrofit has the highest NPV for both the case studies. This means that in the long run, it will be more profitable to invest in level 1 retrofits only.

Benefit/Cost (B/C) ratio was also found for each of the cases by calculating the PW of all the costs and benefits and dividing them. If the B/C ratio is above 1 than it worth it to invest in a project. As seen in table 21, the highest B/C ratios is in the level 1 retrofit for both cases while a level 3 retrofit for the apartment is not feasible at all. This is in line with the results of the NPV worth. While a level 3 retrofit presents the highest amount of energy savings, the NPV and B/C ratio indicate that currently it is not economically feasible to invest in it. A possible explanation is the artificially low electricity prices due to subsidized electricity tariffs due to which reduction in energy usage doesn’t save as much in bills.

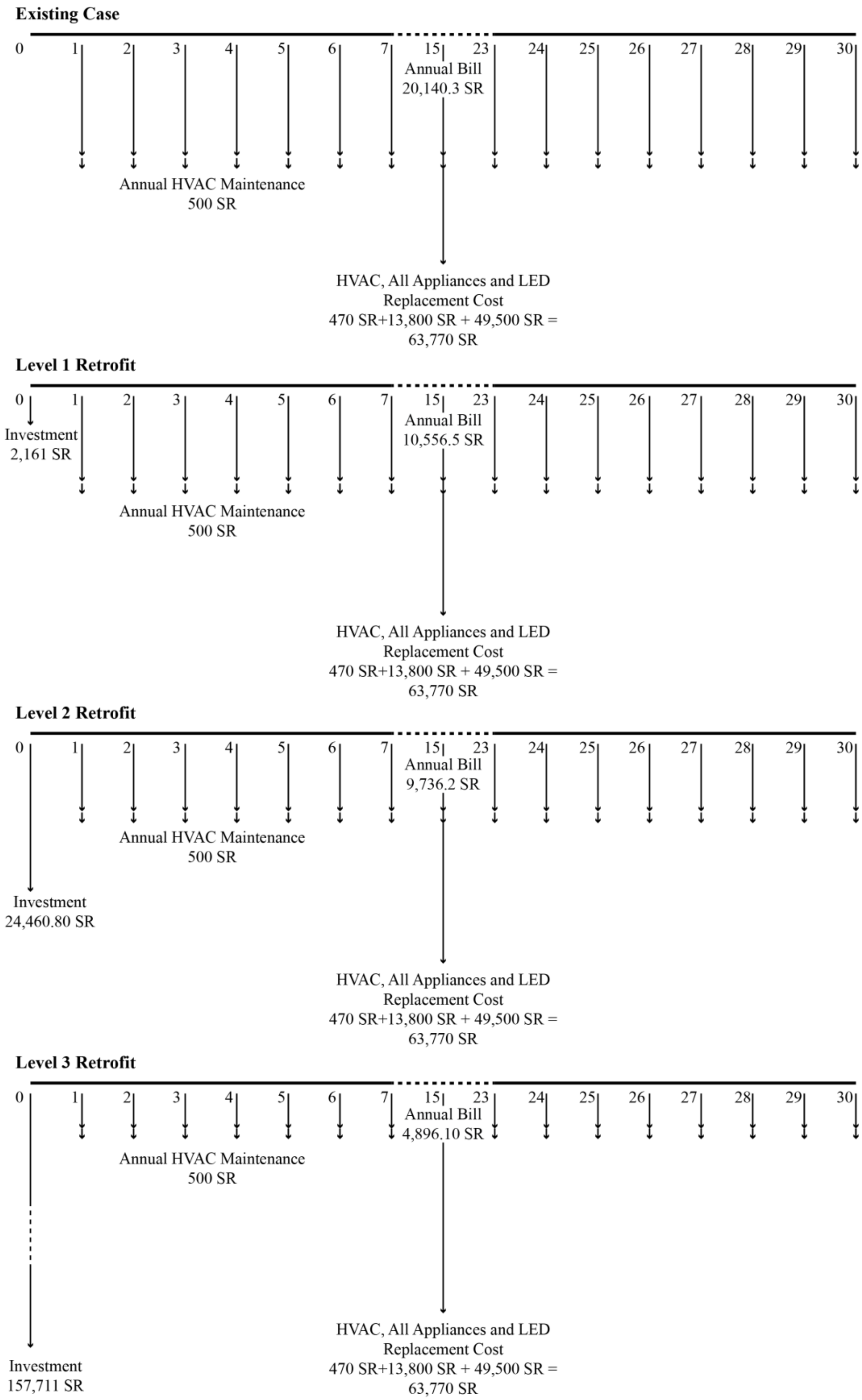


Figure 41: Cash Flow Diagrams of each Retrofit Plan Level of Villa

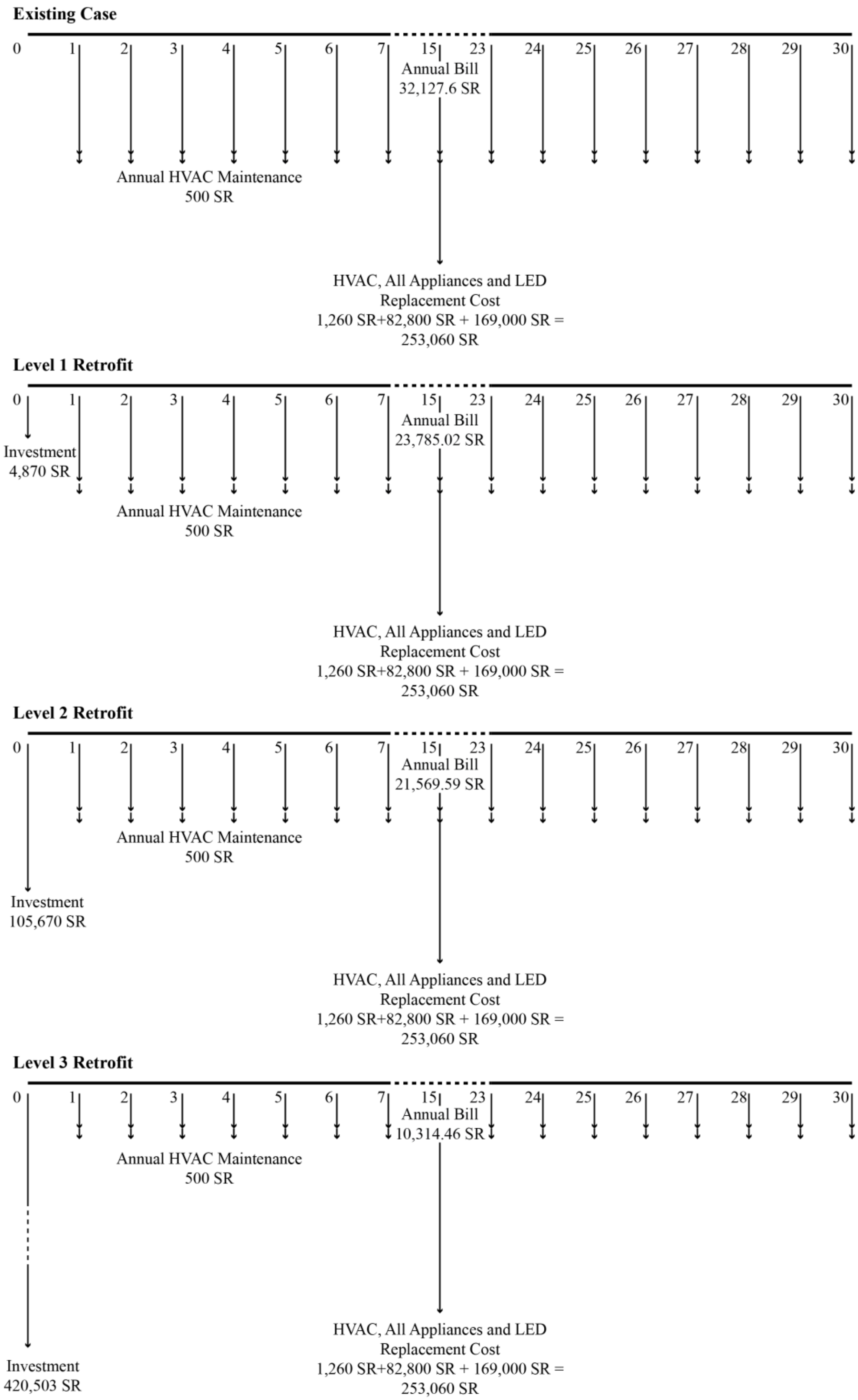


Figure 42: Cash Flow Diagrams of each Retrofit Plan Level of Apartment Building

Table 21: NPV of each Scenario and Savings Compared to Existing

Scenario	NPV (SR)	NPV Savings(SR)	B/C Ratio
Villa			
Existing	-1281670.34	-	-
Level 1	-1106842.21	212,482.58	14.89
Level 2	-1073114	208,556.34	8.52
Level 3	-1097964.61	183,705.73	1.16
Apartment Building			
Existing	-3982387.90	-	-
Level 1	-3800413.308	181,974.59	2.16
Level 2	-3851595.43	130,792.47	1.24
Level 3	-3914352.91	68,034.99	0.15

Next, sensitivity analysis is conducted for three variables as seen in figure 43. It was found that the most sensitive variable to determine NPV is the electricity costs. Hence, an increase in the electricity tariffs by 25% and 50% was suggested and the NPV and B/C ratio for each scenario calculated again (Table 22). We can see as the electricity tariffs are increased, the NPV and B/C results start to make more sense and a level 3 retrofit starts to become more feasible.

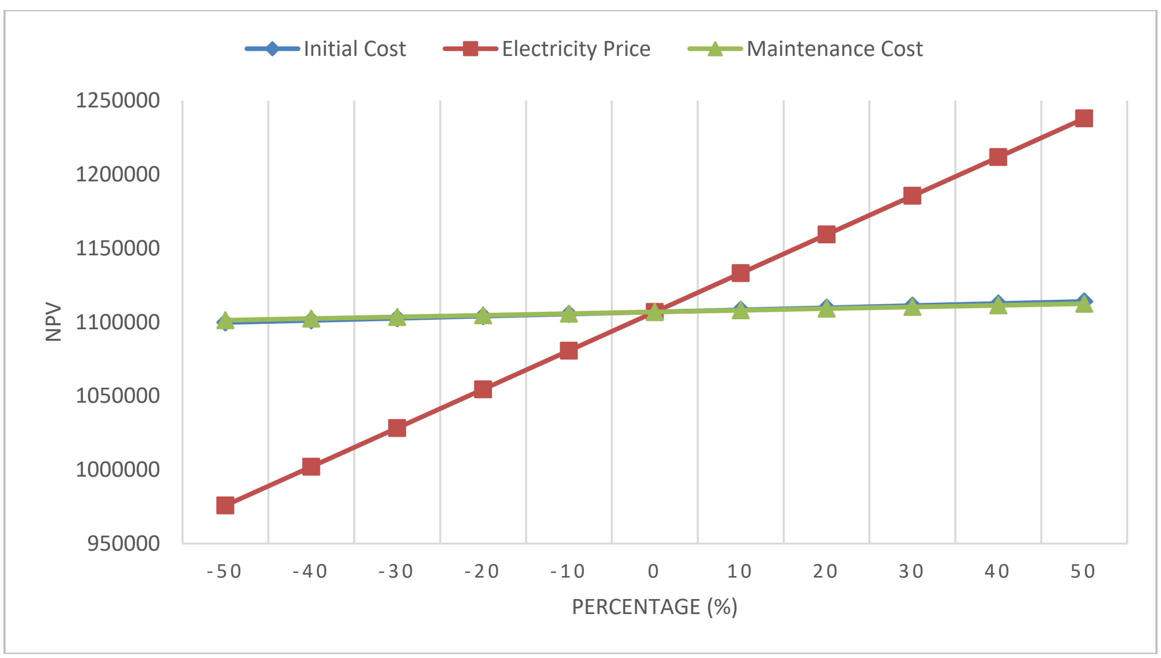


Figure 43: Sensitivity Analysis for the Villa

Table 22: NPV Savings of each Scenario with Increased Electricity Tariff Rates

	25% increase in Tariff			**50% Increase in Tariff**		
Scenario	NPV(SR)	Savings(SR)	B/C Ratio	NPV(SR)	Savings(SR)	B/C Ratio
			Villa			
Existing	1,394,438	0	-	1,507,206	0	-
Level 1	1,128,294	266,143.9	18.65	1,1874,02	319,804.8	22.41
Level 2	1,127,630	266,808.5	10.91	1,182,144	325,062.3	14.39
Level 3	1,125,378	269,060	1.71	1,152,792	354,414.2	2.25
			Apartment Building			
Existing	4,162,274	0	-	4,342,161	0	-
Level 1	3,933,589	228,685.8	2.7	4,066,764	275,396.9	3.28
Level 2	3,972,338	189,936.2	1.79	4,093,103	249,057.4	2.36
Level 3	3,972,105	190,169	0.45	4,029,857	312,303.5	0.74

5.5 Rooftop PV Energy

The energy generation through PV was calculated for both case studies in chapter 3. It was found that for the villa 12,822.6 kWh can be produced annually and for the apartment building 11,840.4 kWh annually. It is not feasible to integrate rooftop PV in the existing case studies as also indicated by (Dehwah et al., 2018). Through the implementation of energy retrofitting, energy consumption of the case studies is reduced, and the offset of PV generation is higher (Table 23). A level 3 retrofit implemented on the villa will reduce energy consumption to a level where the generated energy from PV can cover almost 50% of the demand in the villa, and 21.24% in the apartment building. This is still not feasible for the apartment building but for the villa it is highly feasible and will result in significant economic saving as well. Therefore, it is recommended to integrate rooftop PV only after a level 3 retrofit has been implemented.

Table 23: Energy Offset by Rooftop PV Application in Existing Case and Retrofitted Cases

Scenario	**Annual Energy Consumption (kWh)**	**PV Generation (kWh/year)**	**Energy Offset by PV (%)**
Villa			
Existing	63111	12822.6	20.32
Level 1	54408.63		23.57
Level 2	50948.09		25.17
Level 3	27200.53		47.14
Apartment Building			
Existing	134479.04	11840.4	8.80
Level 1	103762.91		11.41
Level 2	95675.90		12.38
Level 3	55756.60		21.24

5.6 Environmental Analysis

The amount of CO2 emission reduction is calculated for all the scenarios. Through the current level of energy consumption the villa is responsible for 43,231 Kg emission annually while the apartment building is responsible for 92,118.14 Kg annually. Through the implementation of a level 3 retrofit, a reduction of 56.9% and 58.54% is achieved in the villa and apartment building respectively (Table 24). This translates into significant reduction in CO2 emissions and as a result will contribute in improving the environment of the region.

Table 24: CO2 Emission Reduction of Each Retrofit Level

Scenario	Total Energy Consumption (kWh)	Conversion Factor	Total CO2 Emission (Kg/Yr)	CO2 Emission Reduced (%)
Villa				
Existing	63111.00	0.685 Kg/kWh	43231.04	0.00
Level 1 Retrofit	54408.63		37269.91	13.79
Level 2 Retrofit	50948.09		34899.44	19.27
Level 3 Retrofit	27200.53		18632.36	56.90
Apartment Building				
Existing	134479.04	0.685 Kg/kWh	92118.14	0.00
Level 1 Retrofit	103762.91		71077.59	22.84
Level 2 Retrofit	95675.92		65538.01	28.85
Level 3 Retrofit	55756.64		38193.30	58.54

5.7 Final Energy Retrofit Plans

The energy analysis results have indicated that energy retrofitting of existing homes in Eastern Province, Saudi Arabia will lead to significant energy savings. Implementation of the level 3 retrofit plan has the potential to reduce energy consumption by 56.9% and 58.54% annually in villas and apartment buildings in Eastern Province, Saudi Arabia respectively (Table 25). This translates into significant reduction in electricity bills and annually economic savings are achievable. The implementation will also result in significant reduction in CO2 emission levels of each case study.

Table 25: Energy Retrofit Plan Summary

Scenario	Final EUI	EUI Reduced (%)	Capital Cost (SR)	Annual Savings (SR)	Compound Payback (Years)	NPV Savings (SR)	CO2 Emission Reduced (%)
Villa							
Existing	146.8	0	-	0	-	0	0
Level 1 Retrofit	126.5	13.8	2,161	9,583.8	0.23	212,482.6	13.8
Level 2 Retrofit	118.5	19.3	24,460.8	10,404.1	2.43	208,556.3	19.3
Level 3 Retrofit	63.3	56.9	157,711	15,244.2	11.71	183,705.7	56.9
Apartment							
Existing	172.4	0	-	0	-	0	0
Level 1 Retrofit	133.0	22.8	4,870	8,342.6	0.60	181,974.6	22.8
Level 2 Retrofit	122.7	28.9	10,5670	10,559.0	11.27	130,792.5	28.9
Level 3 Retrofit	71.5	58.5	420,503.6	21,813.1	24.60	68,034.9	58.5

The economic analysis however has indicated a contradicting result and that the feasibility of implementing each level is different in the villa and apartment building. The proposed retrofit levels can be summarised as follows:-

1. Level 1-(Low Cost EEMs): The low cost EEMs will reduce the energy consumption by 19.3% and 28.9% annually in villas and apartment buildings respectively and will save on electricity costs by 9,583.8 SR and 8,342.6 SR annually respectively. It will pay back in 0.23 years for the villa and 0.58 years for the apartment building. The NPV indicates that for the 30 years building lifetime, this level of retrofit will save 212,482.6 SR and 181,974.6 SR for villa and apartment building respectively.

2. Level 2-(Level 1 + Medium Cost EEMs): This retrofit level will reduce the energy consumption by 13.8% and 22.8% annually in villas and apartment buildings respectively and will save on electricity costs by 10,404.1 SR and 10,559.0 SR annually respectively. It will pay back in 2.35 years for the villa and 10.01 years for the apartment building. The NPV indicates that for the 30 years building lifetime, this level of retrofit will save 208,556.3 SR and 130,792.5 SR for villa and apartment building respectively which is less value compared to level 1 retrofit plan.
3. Level 3-(Level 1 + Level 2 + High Cost EEMs): The retrofit level will reduce the energy consumption by 56.9% and 58.5% annually in villas and apartment buildings respectively and will save on electricity costs by 15,244.2 SR and 21,813.1 SR annually respectively. It will pay back in 11.71 years for the villa and 24.60 years for the apartment building. The NPV indicates that for the 30 years building lifetime, this level of retrofit will save 183,705.7 SR and 68,034.9SR for villa and apartment building respectively which is the lowest of all the levels.

The presented retrofit levels can be implemented based on the selection of the owners of the villas and apartment buildings. It is seen that while a level 3 retrofit will reduce the energy consumption the most, it is not the most cost-effective for the 30 years of the building lifecycle. Hence, it may not be wise to invest into a level 3 retrofit program comprising of all the EEMs unless the electricity tariffs are increased by at least more than 50%.

Region wide implementation of the retrofit levels can be considered by the municipalities in the Eastern Region by proposing incentives to villa and apartment building owners in the region. According to the 2010 statistics (GASTAT, 2010), there are a total of 161,911 villas and around 41,058 apartment buildings in the eastern region in 2010. Absence of regulations means that these buildings were built before insulation and other energy efficiency regulations were enforced meaning they are in urgent need of retrofitting. Through a level 3 retrofit of all the existing unsustainable villas and apartment buildings in Eastern Region of Saudi Arabia, an overall annual reduction in energy consumption of 9,046.5 GWH is achievable.

CHAPTER 6

CONCLUSIONS AND FUTURE WORK

6.1 Conclusions

Residential sector in Saudi Arabia is consuming the most amount of energy, around 52% of the total national energy. The energy demand in the sector is on the rise and will continue to constantly rise in the business as usual scenario. Typical villas and apartment buildings in the region have a EUI of 150 kWh/Sqm/yr and 198 kWh/Sqm/yr respectively. Years of unsustainable development has led us to a point where we have no other option other than to energy retrofit the existing inefficient homes for a sustainable future.

Previous Global and MENA region studies indicated clearly that individual energy retrofit projects have the potential to reduce energy conservation significantly. A lack of a comprehensive retrofit study is seen in Saudi Arabia as most studies are focusing on large scale retrofit plans' impacts and not on the technical and detailed aspects of energy retrofitting. The aim of this study was to assess the technological and economic aspects of energy retrofitting trends in the residential sector of Eastern Province, Saudi Arabia and ultimately present an economically viable and practical energy retrofit plan suitable for application on existing homes.

A total of eight EEMs were identified as the potential ones to be effectively and practically applied in Saudi Arabia residential buildings including, increasing cooling set point temperature, using energy efficient housing appliances, replacing conventional lights with led, applying window shading, improving glazing type, improving air tightness, using more efficient HVAC system and adding envelope insulation.

In addition, importance of HVAC system maintenance regimes was discussed and a survey was conducted to identify standard HVAC maintenance practices in residential buildings in Saudi Arabia. The survey found that for cooling an average temperature of 20◦C is set in the houses which is lower than the recommended temperature and is a cause of excessive energy consumption. Furthermore, it was found that existing practice is not following the recommended maintenance regimes and inspection and maintenance of majority of the components is conducted as a corrective measure only. This has adverse effects on the HVAC system and a proper maintenance regime needs to be implemented for the complete success of energy retrofitting.

A BIM based framework for retrofitting existing buildings was proposed and investigated in a limited application to two selected case studies, a villa and apartment building in Eastern Province, Saudi Arabia. It indicated that existing homes can be effectively retrofitted through the aid of a BIM framework. The studied showed how the visualization and data capabilities of BIM can be used to design and evaluate EEMs from an architectural and construction point of view. Interoperability between BIM and BEM was also discussed.

A retrofit plan was proposed and the EEMs were categorized in it into three levels based on the initial costs. Results indicate that annual energy consumption in a villa is reduced by 13.79%, 19.27% and 56.9% and in the apartment building by 22.84%, 28.85% and 58.5% for level 1, 2 and 3 retrofit respectively. CPP of implementing each retrofit level was calculated and in a villa investing in level 1, 2 and 3 retrofit will pay back in 0.23, 2.43

and 11.71 years respectively. For the apartment building, the payback period is 0.60, 11.27 and 24.60 years respectively.

The study indicates significant energy and environment benefits of energy retrofitting existing homes in Eastern Province, Saudi Arabia. Overall in Eastern Region, implementation of the level 3 retrofit on existing unsustainable villas and apartment buildings will result in energy consumption reduction of 9,046.5 GWH annually transforming the residential sector into a more sustainable sector.

6.2 Future Work

The study examined energy retrofitting trends in residential buildings in Saudi Arabia through the limited application of a BIM based framework. BIM is a new area of research and a BIM-based framework for energy retrofitting existing buildings has a very wide scope and range of topics which need to be investigated on a global and regional level. For example, data acquisition of existing buildings for the purpose of BIM modelling needs to be investigated in Saudi Arabia as most existing buildings have no available documentation which are required to develop the BIM model. Hence, new techniques of data capturing should be investigated. Furthermore, energy analysis on the BIM model can be conducted in three main ways and in each way there are multiple software which can be used. Accuracy, ease of use and applicability based on local know-how should be studied to build upon the one way which was presented in this study. In the end, a complete BIM based computer application is possible to be developed in collaboration with programmers and other professionals which will input existing building data, develop the BIM model, conduct energy and economic analysis and output the best applicable EEMs on the specific building.

References

Abd-ur-Rehman, H. M., Al-Sulaiman, F. A., Mehmood, A., Shakir, S., & Umer, M. (2018). The potential of energy savings and the prospects of cleaner energy production by solar energy integration in the residential buildings of Saudi Arabia. *Journal of Cleaner Production*, *183*, 1122–1130. https://doi.org/10.1016/J.JCLEPRO.2018.02.187

ACCA. (2013). *Maintenance of Residential HVAC Systems-ACCA Standard 4*. Retrieved from www.acca.org

Achtnicht, M., & Madlener, R. (2014). Factors influencing German house owners' preferences on energy retrofits. *Energy Policy*, *68*, 254–263. https://doi.org/10.1016/J.ENPOL.2014.01.006

AECOM. (2018). *Middle East Handbook*. Retrieved from https://www.aecom.com/middle-east-handbook/

Ahmad, A. (2004). 13 energy simulation for a typical house built with different types of masonry building materials. *The Arabian Journal for Science and Engineering*, *29*. Retrieved from https://www.researchgate.net/profile/Aftab_Ahmad15/publication/229041919_Energy_Simulation_for_a_Typical_House_Built_with_Different_Types_of_Masonry_Building_Materials/links/0046352b28d50092b9000000.pdf

Akbari, H., Morsy, M. ., & Al-Baharna, N. (1996). Electricity Savings Potentials in the Residential Sector of Bahrain. Retrieved from https://aceee.org/files/proceedings/1996/data/papers/SS96_Panel1_Paper02.pdf

Al-Ashwal, Nagib, T., & Budaiwi, Ismail, M. (2011). Energy savings due to daylight and artificial lighting integration in office buildings in hot climate. *International Journal of Energy an d Environment*, *2*(6), 999–1012. Retrieved from www.ijee.ieefoundation.org

Al-Homoud, M. S. (2004). The Effectiveness of Thermal Insulation in Different Types of Buildings in Hot Climates. *Journal of Thermal Envelope and Building Science*, *27*(3), 235–247. https://doi.org/10.1177/1097196304038368

Al-Mofeez, I. A. (2007). Electrical Energy Consumption Pre and Post Energy Conservation Measures: A Case Study of One-story House in Dhahran, Saudi Arabia. *Arch. & Plann*, *19*(2), 1–12. Retrieved from https://cap.ksu.edu.sa/sites/cap.ksu.edu.sa/files/imce_images/jap_ksu_2007_e1.pdf

Al-Ragom, F. (2003). Retrofitting residential buildings in hot and arid climates. *Energy Conversion and Management*, *44*(14), 2309–2319. https://doi.org/10.1016/S0196-8904(02)00256-X

Al-Saadi, S. N., & Budaiwi, I. M. (2007). *Performance-based envelope design for residential buildings in hot climates*. *Building Simulation 2007, BS 2007*. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-

78650266116&partnerID=40&md5=82907365ce301e14db8177e007db265c

Al-Saadi, S. N. J., Al-Hajri, J., & Sayari, M. A. (2017). Energy-Efficient Retrofitting Strategies for Residential Buildings in hot climate of Oman. *Energy Procedia*, *142*, 2009–2014. https://doi.org/10.1016/j.egypro.2017.12.403

Al-Shaalan, A. M. (2012). EER Improvement for Room Air-Conditioners in Saudi Arabia. *Energy and Power Engineering*, *4*, 439–446. https://doi.org/10.4236/epe.2012.46058

Al-Widyan, M. I., & Al-Oqla, F. M. (2014). Selecting the most appropriate corrective actions for energy saving in existing buildings A/C in hot arid regions. *Building Simulation*, *7*, 537–545. https://doi.org/10.1007/s12273-013-0170-3

Al kanani, A., Dawood, N., & Vukovic, V. (2017). Energy Efficiency in Residential Buildings in the Kingdom of Saudi Arabia. In *Building Information Modelling, Building Performance, Design and Smart Construction* (pp. 129–143). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-50346-2_10

Al Surf, M., & Mostaafa, L. (2017). Will the Saudi's 2030 Vision Raise the Public Awareness of Sustainable Practices? *Procedia Environmental Sciences*, *37*, 514–527. https://doi.org/10.1016/j.proenv.2017.03.026

Alaidroos, A., & Krarti, M. (2015). Optimal design of residential building envelope systems in the Kingdom of Saudi Arabia. *Energy and Buildings*, *86*, 104–117. https://doi.org/10.1016/j.enbuild.2014.09.083

Alajlana, S. ., Smiaia, M. ., & Elania, U, A. (1998). Effective tools toward electrical energy conservation in Saudi Arabia. *Energy Conversion and Management*, *39*(13), 1337–1349. https://doi.org/10.1016/S0196-8904(98)00014-4

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

Alexander Friess, W., Rakhshan, K., A.Hendawi, T., & Tajerzadeh, S. (2012). Wall insulation measures for residential villas in Dubai: A case study in energy efficiency. *Energy and Buildings*, *44*, 26–32. https://doi.org/10.1016/j.enbuild.2011.10.005

AlFaris, F., Juaidi, A., & Manzano, F. (2016). Energy retrofit strategies for housing sector in the arid climate. *Energy and Buildings*, *131*, 158–171. https://doi.org/10.1016/j.enbuild.2016.09.016

Algarni, S. (2018). Potential for cooling load reduction in residential buildings using cool roofs in the harsh climate of Saudi Arabia. *Energy & Environment*, 0958305X1878734. https://doi.org/10.1177/0958305X18787340

Aljundi, K., Pinto, A., & Rodrigues, F. (2016). Energy Analysis Using Cooperation between BIM Tools (Revit and Green Building Studio) and Energy Plus. In *1º Congresso Português de Building Information Modelling*. Retrieved from https://www.researchgate.net/profile/Kamar_Aljundi/publication/320471431_Energy_analysis_using_cooperation_between_BIM_tools_Revit_and_Green_Building_St udio_and_EnergyPlus/links/59e75f154585152d5f04e685/Energy-analysis-using-cooperation-between-BIM-tools-

Alrashed, F., & Asif, M. (2012). Challenges Facing the Application of Zero-Energy Homes in Saudi Arabia: Construction Industry and User Perspective. Retrieved from http://www.uksacb.org/sites/default/files/Conference 02-2.pdf

Alrashed, F., & Asif, M. (2014). Trends in Residential Energy Consumption in Saudi Arabia with Particular Reference to the Eastern Province. *Journal of Sustainable Development of Energy, Water and Environment Systems*, *2*(4), 376–387. https://doi.org/10.13044/j.sdewes.2014.02.0030

Alrashed, F., & Asif, M. (2015a). An Exploratory of Residents' Views Towards Applying Renewable Energy Systems in Saudi Dwellings. *Energy Procedia*, *75*, 1341–1347. https://doi.org/10.1016/j.egypro.2015.07.207

Alrashed, F., & Asif, M. (2015b). Analysis of critical climate related factors for the application of zero-energy homes in Saudi Arabia. *Renewable and Sustainable Energy Reviews*, *41*, 1395–1403. https://doi.org/10.1016/j.rser.2014.09.031

AlRashed, F., & Asif, M. (2012). Prospects of Renewable Energy to Promote Zero-Energy Residential Buildings in the KSA. *Energy Procedia*, *18*, 1096–1105. https://doi.org/10.1016/j.egypro.2012.05.124

Alyousef, Y., & Abu-Ebid, M. (2012). Energy Efficiency Initiatives for Saudi Arabia on Supply and Demand Sides. *INTECH*, *3*. Retrieved from http://www.intechopen.com/books/energy-efficiency-a-bridge-to-low-carbon-economy

Ander, D. G. (2016). Windows and Glazing. Retrieved November 8, 2018, from https://www.wbdg.org/resources/windows-and-glazing

ANSI/ASHRAE/ACCA. (2012). *Standard Practice for Inspection and Maintenance of Commercial Building HVAC Systems*. Retrieved from www.ashrae.org/technology.

Asif, M. (2016). Growth and sustainability trends in the buildings sector in the GCC region with particular reference to the KSA and UAE. *Renewable and Sustainable Energy Reviews*, *55*, 1267–1273. https://doi.org/10.1016/J.RSER.2015.05.042

Asif, M., Dehwah, A., Ashraf, F., Khan, H., Shaukat, M., & Hassan, M. (2017). Life Cycle Assessment of a Three-Bedroom House in Saudi Arabia. *Environments*, *4*(3), 52. https://doi.org/10.3390/environments4030052

Autodesk. (2018). Revit | BIM Software. Retrieved November 10, 2018, from https://www.autodesk.com/products/revit/overview

Ben, H., & Steemers, K. (2014). Energy retrofit and occupant behaviour in protected housing: A case study of the Brunswick Centre in London. *Energy and Buildings*, *80*, 120–130. https://doi.org/10.1016/j.enbuild.2014.05.019

Benningfield. (2009). U.s. multifamily energy efficiency potential by 2020. Retrieved from http://energyefficiencyforall.org/sites/default/files/Final_MF_EE_Potential_Report_Oct_2009_v2.pdf

Bogenstätter, U. (2010). Prediction and optimization of LCC in early design. *Building Research & Information*, *28*, 5–6. https://doi.org/10.1080/096132100418528

BPIE. (2011). Renovating the EU building stock | Buildings Performance Institute Europe. Retrieved December 18, 2017, from http://bpie.eu/focus-areas/renovating-the-eu-building-stock/

Budaiwi, I. M., Abdou, A. A., & Al-Homoud, M. S. (2013). Envelope retrofit and air-conditioning operational strategies for reduced energy consumption in mosques in hot climates. *Building Simulation*, *6*(1), 33–50. https://doi.org/10.1007/s12273-012-0092-5

Cassino, K. E., Bernstein, H. M., Asce, F., Senior Director, L. A., Burleigh Morton, A., Partyka Production Manager Alison Lorenz, D., & Gilmore, D. (n.d.). Business Case for Energy Efficient Building Retrofit and Renovation. *McGraw-Hill Construction* . Retrieved from https://www1.eere.energy.gov/buildings/publications/pdfs/alliances/business_case_for_energy_efficiency_retrofit_renovation_smr_2011.pdf

Concrete Construction Magazine. (n.d.). *Estimating Labor Unit Data for Concrete Construction*. Retrieved from https://www.concreteconstruction.net/business/estimating-labor-unit-data-for-concrete-construction_o

Dehwah, A. H. A., Asif, M., & Rahman, M. T. (2018). Prospects of PV application in unregulated building rooftops in developing countries: A perspective from Saudi Arabia. *Energy and Buildings*, *171*, 76–87. https://doi.org/10.1016/j.enbuild.2018.04.001

DOE. (n.d.). Retrofit Existing Buildings | Department of Energy. Retrieved December 18, 2017, from https://energy.gov/eere/buildings/retrofit-existing-buildings

Dubey, K., Howarth, N., & Krarti, M. (2016). Evaluating Building Energy Efficiency Investment Options for Saudi Arabia Retrieved from https://www.kapsarc.org/wp-content/uploads/2016/10/KS-1655-DP049A-Evaluating-Building-Energy-Efficiency-Investment-Options-for-SA_web.pdf

Dubey, K., & Krarti, M. (2017). An Evaluation of High Energy Performance Residential Buildings in Bahrain. *KAPSARC*. Retrieved from https://www.kapsarc.org/wp-content/uploads/2017/07/KS-2017-DP016-An-Evaluation-of-High-Energy-Performance-Residential-Buildings-in-Bahrain.pdf

Energy retrofits | Natural Resources Canada. (2017). Retrieved December 18, 2017, from https://www.nrcan.gc.ca/energy/efficiency/buildings/eeeb/retrofit/4111

Evola, G., & Margani, G. (2016). Renovation of apartment blocks with BIPV: Energy and economic evaluation in temperate climate. *Energy and Buildings*, *130*, 794–810. https://doi.org/10.1016/j.enbuild.2016.08.085

Fasiuddin, M., Budaiwi, I., & Abdou, A. (2010). Zero-investment HVAC system operation strategies for energy conservation and thermal comfort in commercial buildings in hot-humid climate. *International Journal of Energy Research*, *34*(1), 1–19. https://doi.org/10.1002/er.1547

Freedman, A. (2013). Climate Projections More Confident, Dire From IPCC | Climate Central. Retrieved December 18, 2017, from http://www.climatecentral.org/news/ipcc-report-shows-climate-scientists-more-confident-dire-in-projections-165

Fuller, S. (2016). Life-Cycle Cost Analysis. Retrieved December 28, 2017, from https://www.wbdg.org/resources/life-cycle-cost-analysis-lcca

Gamtessa, S. F. (2013). An explanation of residential energy-efficiency retrofit behavior in Canada. *Energy and Buildings*, *57*, 155–164. https://doi.org/10.1016/j.enbuild.2012.11.006

GASTAT. (2010). *The General Population and Housing Census Saudi Arabia 2010*. Retrieved from https://www.stats.gov.sa/en/13

Ghabra, N., Rodrigues, L., & Oldfield, P. (2017). The impact of the building envelope on the energy efficiency of residential tall buildings in Saudi Arabia. *International Journal of Low-Carbon Technologies*, *12*(4), 411–419. https://doi.org/10.1093/ijlct/ctx005

Harriman, C. (2014). What is gbXML. Retrieved March 29, 2018, from https://github.com/chiensiTB/gbXMLValidator/wiki/What-is-gbXML

Hens, H. (2010). Energy efficient retrofit of an end of the row house: Confronting predictions with long-term measurements. *Energy and Buildings*, *42*(10), 1939–1947. https://doi.org/10.1016/j.enbuild.2010.05.030

Holladay, M. (2010). The Energy-Efficiency Pyramid |. Retrieved December 18, 2017, from http://www.greenbuildingadvisor.com/blogs/dept/musings/energy-efficiency-pyramid

IEA. (2013). World Energy Outlook 2013. Retrieved from https://www.iea.org/publications/freepublications/publication/WEO2013.pdf

IEA. (2014). Electric power consumption (kWh per capita) | Data. Retrieved from https://data.worldbank.org/indicator/eg.use.elec.kh.pc

Ilter, D., & Ergen, E. (2015). BIM for building refurbishment and maintenance: current status and research directions. *Structural Survey*. Retrieved from http://www.emeraldinsight.com/doi/pdfplus/10.1108/SS-02-2015-0008

Jang, H., Jones, L., & Kang, J. (2015). Prioritisation of old apartment buildings for energy-efficient refurbishment based on the effects of building features on energy consumption in South Korea. *Energy and Buildings*, *96*, 319–328. https://doi.org/10.1016/j.enbuild.2015.03.027

Jones, P., Li, X., Perisoglou, E., & Patterson, J. (2017). Five energy retrofit houses in South Wales. *Energy and Buildings*, *154*, 335–342. https://doi.org/10.1016/j.enbuild.2017.08.032

KAPSARC. (2016a). KAPSARC Data Portal — Building Permits Issued by Municipalities by Regions and Type of Permit 1987-2015. Retrieved November 18, 2017, from https://datasource.kapsarc.org/explore/dataset/building-permits-issued-by-municipalities-by-regions-and-type-of-permit-1987-

201/?disjunctive.region&disjunctive.building_type

KAPSARC. (2016b). KAPSARC Data Portal — Electricity Consumption by Sectors. Retrieved November 18, 2017, from https://datasource.kapsarc.org/explore/dataset/electricity-consumption-by-sectors/analyze/?disjunctive.region&disjunctive.type_of_consumption

KCORP. (2013). *Housing the Growing Population of Saudi Arabia | Mortgage Loan | Affordable Housing*. Retrieved from https://www.scribd.com/document/331574314/Housing-the-Growing-Population-of-Saudi-Arabia

Khaddaj, M., & Srour, I. (2016). Using BIM to Retrofit Existing Buildings. *Procedia Engineering*, *145*, 1526–1533. https://doi.org/10.1016/J.PROENG.2016.04.192

Khan, M., Asif, M., & Stach, E. (2017). Rooftop PV Potential in the Residential Sector of the Kingdom of Saudi Arabia. *Buildings*, *7*(2), 46. https://doi.org/10.3390/buildings7020046

Kmeťková, J., & Krajčík, M. (2015). Energy Efficient Retrofit and Life Cycle Assessment of an Apartment Building. *Energy Procedia*, *78*, 3186–3191. https://doi.org/10.1016/J.EGYPRO.2015.11.778

Konstantinou, T., & Knaack, U. (2011). Refurbishment of Residential Buildings: A Design Approach to Energy-Efficiency Upgrades. *Procedia Engineering*, *21*, 666–675. https://doi.org/10.1016/j.proeng.2011.11.2063

Krarti, M. (2015). Evaluation of large scale building energy efficiency retrofit program in Kuwait. *Renewable and Sustainable Energy Reviews*, *50*, 1069–1080. Retrieved from https://ac.els-cdn.com/S1364032115005341/1-s2.0-S1364032115005341-main.pdf?_tid=44503e98-d337-11e7-a9b9-00000aab0f6b&acdnat=1511762186_b314c02d9b8159f6e1ca94226fd057e9

Krarti, M., & Ihm, P. (2016). Evaluation of net-zero energy residential buildings in the MENA region. *Sustainable Cities and Society*, *22*, 116–125. https://doi.org/10.1016/J.SCS.2016.02.007

Kuusk, K., & Kalamees, T. (2015). nZEB Retrofit of a Concrete Large Panel Apartment Building. *Energy Procedia*, *78*, 985–990. https://doi.org/10.1016/j.egypro.2015.11.038

Leal, V. M. S., Granadeiro, V., Azevedo, I., & Boemi, S.-N. (2014). Energy and economic analysis of building retrofit and energy offset scenarios for Net Zero Energy Buildings. *Advances in Building Energy Research*, *9*. https://doi.org/10.1080/17512549.2014.944567

Mahmoud, A., Asif, M., Hassanain, M., Babsail, M., & Sanni-Anibire, M. (2017). Energy and Economic Evaluation of Green Roofs for Residential Buildings in Hot-Humid Climates. *Buildings*, *7*(4), 30. https://doi.org/10.3390/buildings7020030

Martinez, A. (2012). *Facade retrofit: enhancing energy performance in existing buildings :: University of Southern California Dissertations and Theses*. Retrieved from http://digitallibrary.usc.edu/cdm/ref/collection/p15799coll3/id/352554

McArthur, J. J. (2015). A Building Information Management (BIM) Framework and Supporting Case Study for Existing Building Operations, Maintenance and Sustainability. *Procedia Engineering*, *118*, 1104–1111. https://doi.org/10.1016/J.PROENG.2015.08.450

Miller, W., Liu, L. A., Amin, Z., & Gray, M. (2018). Involving occupants in net-zero-energy solar housing retrofits: An Australian sub-tropical case study. *Solar Energy*, *159*, 390–404. https://doi.org/10.1016/J.SOLENER.2017.10.008

Mordue, S. (n.d.). *Opportunities and Threats: Definition On BIM-ACE*. Retrieved from http://www.iso.org/iso/catalogue_detail.htm?csnumber=57613

Mujeebu, M., & Al Shamrani, O. (2016). Prospects of energy conservation and management in buildings – The Saudi Arabian scenario versus global trends. *Renewable and Sustainable Energy Reviews*, *58*, 1647–1663. https://doi.org/10.1016/J.RSER.2015.12.327

Okakpu, A., GhaffarianHoseini, A., Tookey, J., Haar, J., Ghaffarianhoseini, A., & Rehman, A. (2018). A proposed framework to investigate effective BIM adoption for refurbishment of building projects. *Architectural Science Review*, *61*(6), 467–479. https://doi.org/10.1080/00038628.2018.1522585

Paradis, R. (2016). Retrofitting Existing Buildings to Improve Sustainability and Energy Performance | WBDG Whole Building Design Guide. Retrieved December 5, 2017, from https://www.wbdg.org/resources/retrofitting-existing-buildings-improve-sustainability-and-energy-performance

Ravetz, J. (2008). State of the stock—What do we know about existing buildings and their future prospects? *Energy Policy*, *36*(12), 4462–4470. https://doi.org/10.1016/J.ENPOL.2008.09.026

Richards, M. (2015). LED Light Bulbs Vs. CFL Light Bulbs: Which is Best for Me? Retrieved November 8, 2018, from https://www.earthled.com/blogs/light-2-0-the-earthled-blog-led-lighting-news-tips-reviews/35906628-led-light-bulbs-vs-cfl-light-bulbs-which-is-best-for-me

Sahin, A. Z., & Rehman, S. (2012). Economical Feasibility of Utilizing Photovoltaics for Water Pumping in Saudi Arabia. *International Journal of Photoenergy*, *2012*, 1–9. https://doi.org/10.1155/2012/542416

Said, S. A. ., Habib, M. ., & Iqbal, M. . (2003). Database for building energy prediction in Saudi Arabia. *Energy Conversion and Management*, *44*(1), 191–201. https://doi.org/10.1016/S0196-8904(02)00042-0

Saleh, M. A. E. (1990). Impact of thermal insulation location on buildings in hot dry climates. *Solar & Wind Technology*, *7*(4), 393–406. https://doi.org/10.1016/0741-983X(90)90024-V

Sanhudo, L., Ramos, N. M. M., Poças Martins, J., Almeida, R. M. S. F., Barreira, E., Simões, M. L., & Cardoso, V. (2018). Building information modeling for energy retrofitting – A review. *Renewable and Sustainable Energy Reviews*, *89*, 249–260. https://doi.org/10.1016/J.RSER.2018.03.064

Scanlan, V. (2010). What is a Deep Energy Retrofit? Retrieved December 18, 2017, from https://www.energycircle.com/blog/2010/03/11/what-deep-energy-retrofit-experts-nesea-conference-respond

Schlomann, B., Isi, F., Faberi, S., Fioretto, I. M., Piccioni, I. N., & Lechtenböhmer, I. S. (2009). *Study on the Energy Savings Potentials in EU Member States, Candidate Countries and EEA Countries*. Retrieved from www.isi.fraunhofer.de

SEEC. (n.d.). Buildings | Saudi Energy Efficiency Center. Retrieved December 18, 2017, from https://www.seec.gov.sa/en

Sidawi, B. (2009). Hindrances to the financing of affordable housing in kingdom of saudi arabia. *Emirates Journal for Engineering Research*, *14*(1), 73–82. Retrieved from http://citeseerx.ist.psu.edu/viewdoc/download;jsessionid=9C038727D0D4E941224CFFF80D0C7A62?doi=10.1.1.304.5712&rep=rep1&type=pdf

Suárez, R., & Fernández-Agüera, J. (2015). Passive energy strategies in the retrofitting of the residential sector: A practical case study in dry hot climate. *Building Simulation*, *8*(5), 593–602. https://doi.org/10.1007/s12273-015-0234-7

Suttel, R. (2006). *Preventive HVAC Maintenance is a Good Investment*. Retrieved from http://www.seedengr.com/Preventive HVAC Maintenance is a Good Investment.pdf

Synnefa, A., Vasilakopoulou, K., Masi, R. F. De, Kyriakodis, G.-E., Londorfos, V., Mastrapostoli, E., … Santamouris, M. (2017). Transformation through Renovation: An Energy Efficient Retrofit of an Apartment Building in Athens. *Procedia Engineering*, *180*, 1003–1014. https://doi.org/10.1016/J.PROENG.2017.04.260

Taleb, H., & Sharples, S. (2011). Developing sustainable residential buildings in Saudi Arabia: A case study. *Applied Energy*, *88*(1), 383–391. https://doi.org/10.1016/J.APENERGY.2010.07.029

Taylor, N. W., Searcy, J. K., & Jones, P. H. (2016). Multifamily energy-efficiency retrofit programs: a Florida case study. *Energy Efficiency*, *9*(2), 385–400. https://doi.org/10.1007/s12053-015-9367-x

Terés-Zubiaga, J., Campos-Celador, A., González-Pino, I., & Escudero-Revilla, C. (2015). Energy and economic assessment of the envelope retrofitting in residential buildings in Northern Spain. *Energy and Buildings*, *86*, 194–202. https://doi.org/10.1016/J.ENBUILD.2014.10.018

Thompson, A. (2014). Major Greenhouse Gas Reductions Needed by 2050: IPCC | Climate Central. Retrieved December 18, 2017, from http://www.climatecentral.org/news/major-greenhouse-gas-reductions-needed-to-curtail-climate-change-ipcc-17300

Thomsen, K. E., Rose, J., Mørck, O., Jensen, S. Ø., Østergaard, I., Knudsen, H. N., & Bergsøe, N. C. (2016). Energy consumption and indoor climate in a residential building before and after comprehensive energy retrofitting. *Energy and Buildings*, *123*, 8–16. https://doi.org/10.1016/J.ENBUILD.2016.04.049

UNEP. (2009). Buildings and Climate Change: Summary for Decision Makers. Retrieved November 18, 2017, from https://europa.eu/capacity4dev/unep/document/buildings-and-climate-change-summary-decision-makers

Weiss, J., Dunkelberg, E., & Vogelpohl, T. (2012). Improving policy instruments to better tap into homeowner refurbishment potential: Lessons learned from a case study in Germany. *Energy Policy*, *44*, 406–415. https://doi.org/10.1016/J.ENPOL.2012.02.006

Wright, A. (2008). What is the relationship between built form and energy use in dwellings? *Energy Policy*, *36*(12), 4544–4547. https://doi.org/10.1016/J.ENPOL.2008.09.014

Zuo, J., & Zhao, Z.-Y. (2014). Green building research–current status and future agenda: A review. *Renewable and Sustainable Energy Reviews*, *30*, 271–281. https://doi.org/10.1016/J.RSER.2013.10.021

Vitae

Name	: Wahhaj Ahmed Yaqub
Nationality	: Pakistani
Date of Birth	:6/15/1994
Email	: wahhaj156@gmail.com
Current Address	: KFUPM, Dhahran 31261, Saudi Arabia
Permanent Address	: 1/555 Shah Faisal Colony, Karachi, Pakistan
Academic Background	: 2016-2018 Masters of Science, Architectural Engineering
	King Fahd University of Petroleum and Minerals
	CGPA: 4.00/4.00
	Focus Area: Building Environmental Control Systems
	2011-2015 Bachelors of Science, Architecture
	King Fahd University of Petroleum and Minerals
	CGPA: 3.62/4.00 (Second Honours)
Publications	: IEEE Conference (Ottawa, Canada)
	Integration of BEM in the design process to improve sustainability standards in the residential sector — Case study of EP, KSA