Faculty of Engineering
Department of Architecture and Built Environment



Transitioning Toward Net-Zero Residential Buildings (N-ZRBs) on the Arabian Gulf Region

(Lessons learned from the Arabian Gulf vernacular architecture)

By
Mosad Alhawas
BSc, MSc.

A thesis submitted to The University of Nottingham in fulfilment of the requirement for the Degree of Doctor of Philosophy
April 2024

Abstract

This research investigates residential building energy performance and feasible energy efficient measures to achieve Net Zero Energy Homes (NZEHs) on the eastern Arabian Gulf peninsula, considering the local vernacular architecture context and passive cooling techniques, regional hot and humid climate conditions, occupants' needs, and cultural requirements. The simple definition of an (NZEH) is when the building is energy-self-sufficient throughout the year. This research investigation has been accomplished through a comprehensively staged research methodology. It included an extensive literature review examining how ancestral communities coped with the harsh climate of the east coast of the Arabian Gulf peninsula in the absence of electricity. Additionally, it involved an analysis of the energy consumption trends in residential buildings within the region, identifying key design characteristics typical to Arabian Gulf residential buildings, and using computer modeling IESVE to illustrate a future Net Zero Energy Home (NZEH) of the region.

The results from computer modeling IESVE of a designed base case indicated that implementing passive cooling ventilation only, such as using natural ventilation through techniques like wind catchers, wind scopes, and an operable door located within a courtyard, produced only marginal reductions in total energy consumption (less than 10%). However, integrating supplementary Energy Efficiency Measures (EEMs), such as enhancing thermal insulation, implementing shading strategies, and improving Heating, Ventilation and Air Conditioning (HVAC) efficiency, led to a further 30% decrease in the building's energy consumption.

While the research shows that achieving annual energy self-sufficiency and reaching Zero Energy Home (ZEH) status is possible in the Arabian Gulf region, it also highlights the challenges. Installing active renewable Photovoltaic (PV) panels on the building's roof is crucial. According to this research investigation, the NZEH concept can be applied to the region, but making it feasible throughout the year is complex. The installation of solar panels made the NZEH energy simulation prototype self-sufficient annually. The definition of an NZE-ready house is when the house reaches a low energy consumption level, which makes it feasible to install solar panels at this stage. For this investigation's 250 m^2 prototype, the total power generated by the PV system during the year was 17.1 MWh, while the NZE-ready house usage was around 16.6 MWh. However, the solar panel system could not meet the total energy demand in the summer months from July to December, with an average deficiency of around 7%. Nevertheless, the PV system has ten batteries with a 4.8 kw/h capacity for each, which can cover this deficit.

Additionally, compared with traditional building construction, the cost penalty of constructing an NZEH increases construction costs by more than 15%, with a payback period of roughly ten years. The increase in the construction cost is mainly due to installing the solar panel systems, which, in the case of this research prototype, cost around $25,000.

Finally, this study contributes to the existing body of knowledge in the field of sustainable building construction by providing a framework, recommendations, and guidelines to promote the adoption of Zero-Energy Homes (ZEHs) in the harsh, hot, and humid climate of the East Coast of the Arabian Gulf and region with smaller climate in general.

Acknowledgement

In memory of my father, who passed away seven years ago, I still hear your voice, gentle and wise, guiding me forward. I still remember when you always said to me, "And he who fears the climb of mountains will live forever among the pits" *(Abual-Qasim AlShabbi,1909-1934)*

The journey of pursuing a PhD abroad, away from my original motherland, has been a serene experience. During this trip, I learned and developed many skills and meanings, such as patience and taking a long breath toward life's tasks. Also, when focusing on enjoying the journey ……. the goal becomes a matter of time.

I sincerely thank my advisor, Dr Rabah Boukhanouf, for being patient and for his unwavering support and guidance throughout the research journey. I am also thankful for the valuable feedback from my second supervisors, Dr Xiaofeng Zheng and Dr Carlos Jimenez. Also, I want to extend my appreciation to the internal assessor, Dr John Calautit, for his comments and assistance in learning the IES energy simulation program.

Many thanks to my family, particularly my mother, to whom I am accountable and have a lifetime obligation for love, care, and affection. Thanks also to my three brothers and three sisters for their support. Thank you all so much for believing in me, and I highly appreciate your continuous encouragement throughout these years. All of you have been part of my success and an inspirational force pushing me to achieve more and aim higher.

Publications

Alhawas, M., Boukhanouf, R., 2023. ' Concept of net-zero-ready residential buildings in the hot-humid region (Lessons learned from the Arabian Gulf vernacular architecture)'. In: Riffat, Su, ed., Sustainable Energy Technologies: Proceedings of the 20th International Conference on Sustainable Energy Technologies, 15th – 17th August 2023, Nottingham. University of Nottingham: Buildings, Energy & Environment Research Group. Pp 217-227. Available from: Nottingham-repository.worktribe.com/ [12/13/2023].

Table of Contents

Abstract II

Acknowledgment IV

Publications V

List of Figures X

List of Tables XV

List of Abbreviations XVII

CHAPTER 1-Introduction 1

1.1-Background 1

1.2- Overview of Domestic Building Distribution 4

1.3-Aim and Objectives 8

1.4-Research Hypothesis and Questions 9

1.5-Research Uniqueness and Contributions 9

1.6-General Methodology 15

1.7-Structure of The Research 15

CHAPTER 2- Review of Vernacular Architecture And Construction Materials In The Gulf Region. 17

2.1- Introduction 17

2.2- Vernacular Passive Colling Techniques 19

2.2.1- Courtyards 19

2.2.2- Windcatcher 20

2.2.3- Massive walls 23

2.2.4- Wind Scoops 24

2.2.5- Basement 25

2.2.6- Ivan 26

2.3 - Vernacular Construction Materials 27

2.3.1- Mud Brick 28

2.3.2- Coral Stone 29

2.3.3- Plaster 30

2.3.4- Palm Trunk 32

2.3.5- Palm Frond 34

2.4- Remarks 35

2.5- Summary 41

CHAPTER 3- Energy Efficient Measures and The Concept of Net-Zero-Energy-Homes (NZEHs) in Hot-Humid Climate 41
3.1- Introduction 42
3.2- Appropriate Energy Efficient Measures (EEMs) 42
3.2.1- Building Shape and Orientation 43
3.2.2- Wall and Roof Insulation 44
3.2.3- Window Shading and Glazing Type 45
3.2.4- Natural Ventilation 47
3.2.5 - Daylighting 49
3.2.6 - Wall and Roof Reflectance 50
3.2.7 - HVAC system efficiency 51
3.2.8- Thermostat Setback. 52
3.2.9- Thermal Mass (Adobe Walls) 52
3.2.10 - Phase Change Materials 54
3.2.11 -Green Roof 56
3.3- The Design Concept of (NZEHs) 57
3.3.1- (NZEHs) Design Components 59
3.3.2-Previous Work 61
Casini-2020 61
Alkhateeb-2019 63
Belpoliti et al-2019 64
Taleb-2014 65
Alrashed 2015 66
Aldossary-2017 66
Alfaris, Juaidi, et al-2017 67
Lan, wood et al-2019 68
Deng et al-2011 69
Feng-2019 70
Rodriguez-Ubinas et al-2014 71
Kristiansen et al, 2019 72
3.4- Remarks 73
3.5- Summary 78
CHAPTER 4- Research Methodology 80
4.1- Introduction 80

4.2- Research philosophy and methods 81
4.3- Research Methodology Stages 83
4.4- Residential building survey 86
4.5- Design of a typical base case 89
4.5.1- Base Case Geometry and Functional Spaces 91
4.5.2- Base Case structure and construction materials 96
4.5.3- Heating, ventilation, and air-conditioning system (HVAC) 100
Demotic Hot Water (DHW) 101
Occupants' Heat Gain and Equipment Power Density 102
Occupancy operation schedule and equipment usage patterns. 103
4.5.4- Electric & Artificial Lighting 103
4.6- Base Case Computer Modelling and Validation 106
4.6.1-Selecting the Energy Simulating Tool 106
Validation of the Energy Simulating Tools. 109
4.6.2-Validation of the Base Case. 113
4.6.3-Comparing the Base Case with Other Researcher Models 115
4.7- Summary 103
CHAPTER 5-Residential Buildings Survey Results 127
5.1-Introduction 128
5.2-Survey Demographics 128
5.3-Residential buildings condition 130
5.3.1- Type and Number of Floors & Internal Spaces 132
5.3.2- Type of Cooling, Heating, and Artificial Lighting Systems 134
5.3.3- Summer & Winter Electricity Bills 138
5.3.4- Building Envelope 139
5.4-Views Towards the Application of ZEHs In Dammam City 140
5.4.1-Views Towards Applying Energy Efficient Measures 142
5.5- Remarks 143
5.6- Summary 145
CHAPTER 6 - Design And Conceptualization of the Net Zero Energy House (NZEH) 146
6.1-Introduction 146
6.2-Designing The Net Zero Energy Home (NZEH) 147

6.2.1- The potential of saving energy 148
6.2.2- NZEH Decision-Making Development 154
Enhancing Building Construction Specification Qualityalidation. 109
Applying Energy Efferent Measures & Sustainable Design Features. 109
Window Shading. 157
Natural Ventilation. 109
Building Shape and Orientation 109
Daylighting. 109
HVAC Efficiency & Thermostat Setback Point. 109
6.2.3- NZEH Prototype Final Design 154
Applying solar panel system 154
6.4- NZE Prototype Added Cost Estimation. 175
6.5- NZE Prototype NZE Prototype CO2 Reduction through Energy Savings. 177
6.6- NZE Prototype Payback Period. 179
6.7- Summary 181
CHAPTER7-DISCUSSION AND CONCLUSION
7.1- Overview 184
7.2- Research Outcomes 185
7.3-The Opportunities and Challenges to Promote NZE Residential Buildings in Saudi Arabia 190
7.4- Recommendation & Final Remarks 193
7.4.1- higher establishment's decision-makers 101
7.4.2- designers and real estate developers 101
7.4.3- clients and home tenants 101
7.5- Research limitations 199
7.6- Future work 200
8- Reference 202
9- Appendix 210
Appendix A: Dammam City Residential Building Survey. 210
Appendix B: Dammam City Residential Building eQuest energy modeling 224
Appendix C: Dammam City Residential Building IES energy modeling data…… .. 225
Appendix D: The Base case energy simulation model for IES & eQuest 226

Appendix E: Actual architecture plans and electricity bills 232
Appendix F: Daylighting dimming profiles. ……..…….……..…..…234
Appendix G: Imaginary perspective for how the NZEH prototype will be. ……...…235

List of Figures

- Chapter one

Figure 1. 1 KSA. Electricity Generation by Energy Source according to us energy information administration..... 1
Figure 1.2 U.S. Electricity Generation by Energy Source according to U.S. Energy Information Administration.. 2
Figure 1.3 GCC Residential Power Demand Split by Building Consumption..... 3
Figure 1.4 Saudi Arabia distribution of households by building material used for house construction (Kingdom of Saudi Arabia General Authority of Statistics, 2019)..... 5
Figure 1. 5 Saudi Arabia distribution of households by building type (Kingdom of Saudi Arabia General Authority of Statistics, 2019)..... 6
Figure 1. 6 Saudi Arabia resident ownership pattern (Kingdom of Saudi Arabia General Authority of Statistics, 2019)..... 7
Figure 1. 7 Synthesis diagram illustrates the Research Uniqueness and Contributions to the field of knowledge. 12
Figure 1.8 general research methodology diagram - is divided into three stages to meet the main research aims and objectives.. 14

- Chapter two

Figure 2. 1 “Albana” the builder is constructing a home using a set of double mud bricks in Kuwait 2014 ,كونا)..... 18

Figure 2. 2 Courtyard Bait al Naboodah in Al-Sharjah-UAE which is opened its doors on November 14, 1995. After its renovation and restoration, Bait Al Naboodah was reopened again on April 08, 2018 (Source: - Sharjah Museums Authority)..... 19
Figure 2. 3 The difference between outdoor and courtyard air temperatures in Yazd, Iran (Heidari 2010). 20
Figure 2. 4 Esa bin Ali house in the Kingdom of Bahrain has a wind tower and courtyard that is surrounded by rooms (Source: - Bahrain Authority for Culture and Antiquities). 21
Figure 2. 5 Stack effect and air buoyancy during the day (Alp, 1991). 21
Figure 2. 6 Cross ventilation through the wind tower to the courtyard at night (Alp, 1991)..... 21
Figure 2.7 A hand drawing for a “Al Bastakiya” house in Dubai shows a wind scoops location (gawhary, 2015). 24
Figure 2. 8 Sheikh Saeed al-Maktoum's House in Dubai was built with a massive mud brick (Adobe walls) (Hantash, 2016). 23

Figure 2. 10 A wind scoops in the wall helps to encourage the air circulation in rooms (Alp, 1990). 24
Figure 2. 11 The section shows how the basement ceiling raises above the ground to allow air circulation to cross throw basement ventilation openings (Haji-Qassemi & Karbassi, 1998)..... 25
Figure 2. 12 Usually, Ivans are linking to rooms and spaces by alleyways (Tavassoli, 1982 as cited in Khalili and Amindeldar 2014)..... 26
Figure 2. 13 Aqil bin Mohammad Al Banna , the last of seven generations of builders. Aqils ancestors migrated from Bastak in Iran to Dubai in the Arabian Gulf, and they used to build homes using mud brick (Hawker 2008)..... 28
Figure 2. 14 This picture was captured in Kuwait at Failaka island in 1940. The picture shown Kuwaiti bannas making mud bricks then they keep it dry by the sun.(2014 ,كونا).... 28
Figure 2. 15 here we can see the coral stone walls. In the right picture, the wall is consisted of two coral stone layers. (Wadi hayl in Fujairah) (Hawker 2008)..... 29
Figure 2. 16 In this winter house any spaces between stones were chinked up with a mud fill (Hawker 2008)..... 30
Figure 2. 17 In this summer house spaces between stones were large to allow the cool wind air flow (Hawker 2008)..... 30
Figure 2. 18 Spectacular plaster work, the Seyyadi house in Muharraq Bahrain. We can see the rounded corner plasterwork and the complex window screen (Hawker 2008)..... 31
Figure 2. 19 Pieces of plaster moulding lie in the interior courtyard of Zaabi winter house in Jazirat Al-Hamra in UAE. The zigzag pattern was made using a wooden template (Hawker 2008)..... 31
Figure 2. 20 A roof supported by palm trunks in Al-Jhra fort in Kuwait (2014 ,كونا). 33
Figure 2. 21 A large door was imported from India, well known for its carving industries. This door in Oman..... 33
Figure 2. 22 This piece of the trunk a part of tree known as Al-Sidr tree usually, they use it to support the roof. The location of this trunk is in Wadi sham - Ras-Alkamah -UAE. (Hawker 2008). 33
Figure 2. 23 Here you can see the palm tree woven leaves (Hasir) is used in the roof construction to hold the wood plates. (Hawker 2008)..... 34
Figure 2. 24 A builder is making (Areesh) house using palm frond.(ابراهيم ,2020) 34
Figure 2. 25 A timeline describing the Arabian Gulf east coast construction and material development between(.1950-1800) 38

- Chapter three

Figure 3.3 This picture was taken for the Keighton Auditorium façade at the University of Nottingham on the 12 of March 2021 at 2;27pm: the shading device falls to protect the window lower part, which is considered as under-sizing in the design process..... 47
Figure 3. 4 Types of pressure that cause air infiltration/exfiltration (stack pressure, wind pressure, fan pressure) (Anas Al-Homsi et al, 2017) 48
Figure 3.5 Airflow movements and pressure distributions in Maos study about HRR buildings. There is no restriction to vertical (floor tofloor) air circulation through the building interior (Mao, 2015)..... 49
Figure 3.6 Potential for energy savings (%) on artificial lighting when using the Ideal Window Area concept combined with an outdoor illuminance of 5000 lux (Ghisi et al, 2005)..... 50

Figure 3.7 Phase Change Materials complete melting-freezing cycle (thermtest, 2020)..... 55
Figure 3. 8 The green roof construction and layers component according to Insulation Corporation of America..... 57
Figure 3.9 Derived from location of renewable energy generation, defined four types of NZEBs: A, B, C and D, (Pless & Torcellini, 2010). 58

Figure 3. 10 NZEHs design steps, showing the energy reduction percentage in each stage. (Maclay, 2014)..... 59
Figure 3. 11 ReStart4Smart ZEH design strategies. (Casini 2020)..... 62
Figure 3. 12 ReStart4Smart geometry design features. (Casini 2020)..... 63
Figure 3.13 Different strategies for installing PV panels and shading elements using (IES VE ModelIT) (Alkhateeb, 2019)..... 63
Figure 3.14 (a) The innovated windcatcher and (b) the buffer zone concept (belpoliti et al 2019) 65
Figure 3. 15 Approach of the adopted passive cooling design strategies (Taleb, 2014). 65
Figure 3. 16 Model and floor plans for virtual house. Alrashed 66
Figure 3. 17 Benchmarking Energy Consumption in kWh/m2 with international standards (Aldossary, 2017) 67
Figure 3. 18 Utilizing solar energy on the roof of the studied home resulting in reducing the annual energy consumption Alfaris, Juaidi, et al. 2017. 68
Figure 3. 19 Floor plan of one floor, floor plan of one unit, and 3D model of apartment building Lan,wood et al. 2019..... 69
Figure 3. 20 Shanghai model's comfort temperature is met even under hot-humid weather. 70
Figure3. 21 Design features and building technology choices of the NZEB cases Feng, 2019. 71
Figure 3. 22 Buildings' passive and hybrid solutions Rodriguez-Ubinas et al. 2014 72
Figure 3. 23 Planning Steps contribute towards zero energy building Kristiansen at el, 2019) 72
Figure 3. 24 Modular off-grid ZEB made from shipping container modules Kristiansen at el, 2019) 73
Figure 3. 25 synthesis diagram summarizes the previous work net zero strategies. 76

- Chapter four

Figure 4.1 Overview for Implementation of the approaches used in this study. 89
Figure 4. 2 The research methodology diagram - is divided into three stages to meet the main research aims and objectives. Each step will require a specific and different conducting tool to answer research questions and fulfil a specified purpose..... 85
Figure 4. 3 Overview for the resident's survey key parameters..... 87
Figure 4.4 The Base case Data collection is taken from four different sources. 89
Figure 4. 5 Base case main designing parameters and key aspects. 90
Figure 4. 6 Murjana Residential Complex showing the buildings geometry (Dammam city). 91
Figure 4. 7 Base case common zoning distribution and privacy levels with spaces synthesis. 92
Figure 4. 8 2D layout of the proposed base case ground floor plan..... 94
Figure 4. 9 2D layout of the proposed base case first floor plan..... 95
Figure 4. 10 2D layout of the proposed base case service floor plan..... 96
Figure 4. 11 NSAAG townhouse project building's envelope construction type (Al Khobar city). 96
Figure 4. 12 Both ASWAR & NSAAG projects building's roof structure type (Al Khobar city)..... 97

Figure 4. 14 Selecting the Energy Simulating Tool and Validating the Base Case simulation prototype process, in four main steps. 106
Figure 4. 15 Dwelling location in the Ash Shulah Dist. Dammam city. 106
Figure 4.16 The dwelling geometry from the IES & eQuest simulation tools & the home actual architecture plan. 110
Figure 4. 17 The existing dwelling 12 months energy consumption bills by Saudi Riyals (SEC, 2021). 111
Figure 4. 18 The predicted annual energy consumption from both programs has been compared with the existing dwelling 12 months energy consumption bills. 113
Figure 4. 19 Actual Building in Dammam city Vs the Base case geometry in eQuest simulation tool. 114
Figure 4. .20 comparing the energy use intensity between the base case model and actual home in Dammam city. 115
Figure 4. 21 compares the energy use intensity between the Saadi et al. model and the base case. 117

- Chapter five

Figure 5. 2 The percentage of marital status based upon age groups..... 129
Figure 5. 3 The average size of family member based upon education level 129
Figure 5. 4 Residential building types and the percentage of current building types 130
Figure 5. 5 Residential building floor area and the percentage of each area groups 130
Figure 5. 6 Residential building contract types and the percentage of each type 131
Figure 5. 7 Residential buildings Construction periods and the percentage of each period 131
Figure 5. 8 Residential buildings home finance method 132
Figure 5. 9 Number and type of internal spaces showing the Min., Max., mean of each space. 133
Figure 5. 10 Number and percentage of residential building floors showing the Min., Max., mean and Std D. 133
Figure 5. 11 The HVAC systems typically used for cooling and the percentage reported for each type. 134
Figure 5. 12 Air conditioning thermostat setback points and the percentage reported for each point. 135
Figure 5. 13 how users behave toward HVAC system energy conservation. 135
Figure 5. 14 HVAC systems typically used for heating and the percentage reported for each type. 136
Figure 5. 15 Artificial lighting systems typically used in homes and the percentage reported for each type. 136
Figure 5. 16 Water heating systems and the percentage reported for each type. 137
Figure 5. 17 How users behave toward water heating system energy conservation. 137
Figure 5. 18 Average monthly summer & winter electricity bills. 138
Figure 5. 19 Building construction systems typically used in the Saudi market and the percentage reported for each type. 139
Figure 5. 20 Windows glazing type and the percentage reported for each type. 140
Figure 5. 21 Measuring the acceptance of applying the idea of NZEHs in Dammam city. 141

Figure 5. 22 Measuring the awareness of energy rating cards for HVAC systems and appliances. 141
Figure 5. 23 Examine the acceptability of sustainable design and energy-efficient measures to investigate the views towards ZEHs. 142

- Chapter six

Figure 6.1 Dammam city NZEH designing stages, which has been broken down into three main phases (author's source)..... 147

Figure 6. 2 IES diagram for base case energy consumption in each building service category....148
Figure 6. 3 IES diagram for base case primary heat gains resources that affects the HVAC load. 149
Figure 6. 4 IES chart for base case primary external heat gain resources 150
Figure 6. 5 IES diagram for base case primary internal heat gain resources 151
Figure 6. 6 base case sensitivity analysis in reference to the specification of the actual home in Dammam city and the net-zero "Restar4" model. 153
Figure 6. 7 base case section showing the building envelope components that will be enhanced and tested. 155
Figure 6. 8 Base Case EUI VS an Enhanced base case Efficiency of 50 % & 100% With the percentage of reduction in each Enhancement..... 156
Figure 6. 9 Base Case SketchUp model on the left and the IES base case model with window shading enhancement to the right.. 157
Figure 6. 10 uses the sun cast feature in IES to determine which is the best shading device that ensures the whole window's coverage without under sizing the design and selection... 158
Figure 6. 11 uses the sun cast feature in IES to determine the suitable window shading device dimensions that is cover the window area from sun in the whole year... 158
Figure 6. 12 IES Base Case solar heat gain on Aug.15 before and after using the windows shading device..... 159
Figure 6.13 IES Base Case's cooling sensible load on Aug.15 before and after using the windows shading device. 160
Figure 6. 14 IES Base Case people's dissatisfaction on Aug.15 before and after using the windows shading device. 160
Figure 6. 15 The base Case has been redesigned by applying a wind catcher, an operable door and wind scopes to introduce cross ventilation to the building..... 161
Figure 6. 16, the base case geometry on the IES energy simulation program, shows the natural ventilation measures introduced to the base case..... 162
Figure 6. 17 IES Microflow analysis feature shows the base case natural airflow movement through the home openings 162
Figure 6. 18 IES formula function profile creation for Windcatcher thermal operating profiles.163
Figure 6. 19 IES Daly profile feature as the first step for creating Windcatcher annual operating profile. Showing the windcatcher operating formula (to<=ta)..... 163
Figure 6. 20 shows the relationship between base case outside temperature, room temperature and natural ventilation. 164
Figure 6. 21 shows the average natural ventilation throughout the year (volume flow) that the home receives from all geometry openings.. 165

Figure 6. 22 compares the building's CO2 emission (kgCO2/h) before and after using natural ventilation 166
Figure 6. 23 shows the relation between CO2 concentration and introducing natural ventilation in the base case on the 15th of December... 166
Figure 6. 24 compares the building's space cooling before and after using natural ventilation..167
Figure 6.25 compares the building's total electricity consumption before and after using natural ventilation. 167
Figure 6. 26 The effect of changing the base case shape and orientation on solar heat gain.....169
Figure 6. 27IES graph showing enhancement for Base Case daylighting distribution through the Flucs-DL feature.. 170
Figure 6. 28 shows the Effect of the Base Case's Energy Efficiency Measures & passive cooling techniques on Energy Saving.. 172
Figure 6.29 Base Case prototype's Solar system design includes batters and inventor requirements.. 173
Figure 6. 30 IES Base Case prototype's Solar panel system arrangements, by free-standing solar panels feature, containing 22 solar panels which cover 23 % of the roof area..... 174
Figure 6. 31The Base case (CO2) emissions were analysed across many categories of the whole building system, including lighting, equipment, and other building systems 178
Figure 6. 32 The NZEH (CO2) emissions were analysed across many categories of the whole building system, including lighting, equipment, grid PV, electricity disruption and other building systems.. 178

- Chapter seven

Figure 7. 1 Total Energy Saving from The Efficiency Measures & Passive Cooling Techniques.. 189
Figure 7.2 NZEH performance during the whole year showing a comparison between the electricity consumption of the base case and the NZE ready case with the PV electricity generation..... 190

List of Tables

- Chapter two

Table 2. 1 Summarises our ancestor's use of ambient environmental phenomena and remarks that have been reflected to inform the research methodology.....35

Table 2. 2 Summary of the passive cooling Techniques matched with their environmental characteristics. 37
Table 2. 3 summary of the construction materials matched with their physical characteristics. . 37

- Chapter three

Table 3. 2 summarises energy-efficient measures that have been discussed in this chapter with some suggestions and limitations..... 74
Table 3. 3 Summaries of NZEHs Previous studies and the remarks that have been reflected to inform the research methodology.. 77

- Chapter Four

Table 4. 1 Base case Mean interior spaces size and number according to Dammam city residential survey and “Sakani “residential program case studies. 93
Table 4. 2 Thermal properties of common materials used in construction in Saudi Arabia (ASHRAE, 2009). 97
Table 4. 3 U-values & descriptions for typical doors and windows construction lyres in Saudi residential buildings. 98
Table 4. 4 U-Values and descriptions for common building construction layers in Saudi residential buildings. 98
Table 4. 5 Building envelop R-value’s requirements according to the Saudi building code 99
Table 4. 6 Building envelop U-values requirements according to the Saudi building code 99
Table 4. 7 Base case HVAC system specifications and code requirements. 100
Table 4. 8 People sensible and latent heat gains depend on the type of occupant zone (ASHRAE, 2009). 102
Table 4. 9 The power densities for main zones in the typical home (Monawar, 2001). 102
Table 4. 10 (EUI) values for residential buildings by KSA region (M. Krarti et al, 2020). 103
Table 4. 11 Base case artificial lighting fixture type and power rating. 104
Table 4. 12The most popular energy simulating programs were analyzed to meet NZEH mandatory requirements. 108
Table 4. 13 Actual dwelling’s building envelop properties and construction elements description. 110
Table 4. 14 New Electricity Tariffs for all building types as approved by the Council of Ministers' Decree dated 12/12/2017, which has been applied since 1/1/2018 (SEC, 2018). 111
Table 4. 15 dwelling 12 months energy consumption bills converted from cost (SR) to consumption (kw/h) using the tariffs rate provided in table 4.3. 112
Table 4.16 compares specifications between the actual home in Dammam city and the base case. 114
Table 4.17 compares specifications between the (Al-Saadi et al., 2007) model and the base case. 116

- Chapter five

Table 5. 1 Survey demographical statistics including profession, age, education, and marital status. 128
Table 5. 2 Summary of the survey findings and remarks. 144

- Chapter six

Table 6. 1 Model specification comparison of the Net Zero Restar4 model, base case, and Actual home.residential survey and “Sakani “residential program case studies. 152
Table 6. 2 base case primary construction specifications with an enhanced efficiency of 50 % and 100%.). 155
Table 6. 3 variety of base case geometry shapes & orientations, including each shape remarks.. 168
Table 6. 4 The improved base case construction specifications &EEMs that have been simulated in the IES tool.s. 172
Table 6. 5 Base case solar panel specification and type, which is linked to IES energy simulation tools..... 174

Table 6. 6 IES table showing a comparison between home electricity consumption & PV electricity generated. ……..175
Table 6.7 NZE prototype added cost estimation for all building components, which was made specifically for this research case, including quantity and market price.. 176
Table 6.8 Compares the yearly carbon dioxide (CO2) emissions of the Base case with a Net Zero Energy Home (NZEH)... 177
Table 6.9 New Electricity Tariffs for all building types as approved by the Council of Ministers' Decree dated 12/12/2017, which has been applied since 1/1/2018 (SEC, 2018).. 180

- Chapter seven

Table 7.1 Final study investigation framework indicating the research finding & and remarks coupled with each measure stage.. 198

List of Abbreviations

NZE: Net Zero Energy

NZEHs: Net Zero Energy Homes

NZEBs: Net Zero Energy Buildings

IESVE: Integrated Environmental Solutions –Virtual Environment

SEC: Saudi Electricity Company

SBC: Saudi Building Code

SASO: The Saudi Standards, Metrology, and Quality Organization

SR: Saudi Riyal

GCC: Gulf Cooperation Council

UAE: United Arab Emirates

GHG : Greenhouse Gas

HVAC: Heating, ventilation and air-conditioning

AC: Air-Conditioning

ACH: Air Change per Hour

AHU: Air Handling Unit

COP: The Coefficient of Performance

ASHRAE: American Society of Heating, Refrigeration, and AirConditioning

PV: Photovoltaic

EUI: Energy Use Intensity

CFD: Computational Fluid Dynamics

WWR: Window-to-wall area ratio

MWh: Mega-Watthour

MW: Megawatt

kW: Kilowatt

PCMs: Phase Change Materials

SHGC: Solar Heat Gain Coefficient

EER: Energy Efficiency Ratio

EEMs: Energy Efficient Measures

U-value: Thermal transmittance

CHAPTER 1

Introduction

1.1-Background

The rise of oil expenditures in the 70s allowed the Gulf Council countries (GCC) to use significant revenues generated from oil production to construct new modern cities and their associated infrastructure and amenities. The oil wealth also has been reflected in considerable changes in lifestyle patterns and living standards. It was found that lifestyle, individual consumer behaviour, and other socio-cultural factors influence energy use in individual dwellings. These have listed the Arabian Gulf Countries among the top 10 countries in terms of electricity consumption and CO_2 emission per capita worldwide. Furthermore, with oil prices fluctuating, and since 80% of our electricity generation is derived from oil as the main energy source, the necessity to diversify the energy resources is becoming vital (see Figure 1.1).

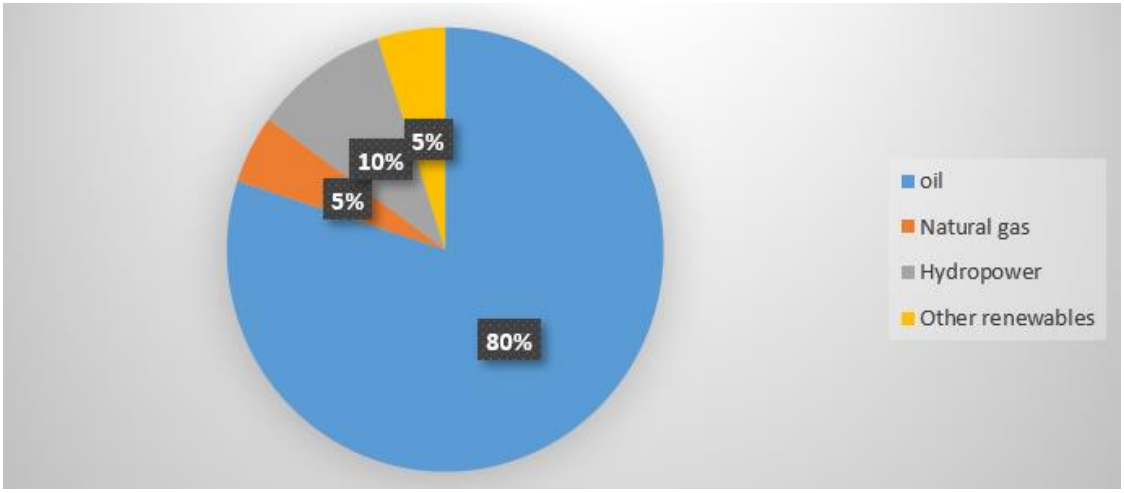


Figure 1.1 KSA. Electricity Generation by Energy Source according to us energy administration.

Comparing our region with other global countries shows it depends mainly on oil as one major energy source. For instance, in the USA, there is a diversity of energy sources they can rely on in case of any energy crisis, including nuclear and renewable energy (see Figure 1.2). However, many significant problems remain, including the harsh climate, resource market instability, and an unplanned expanding rate of new housing unit construction.

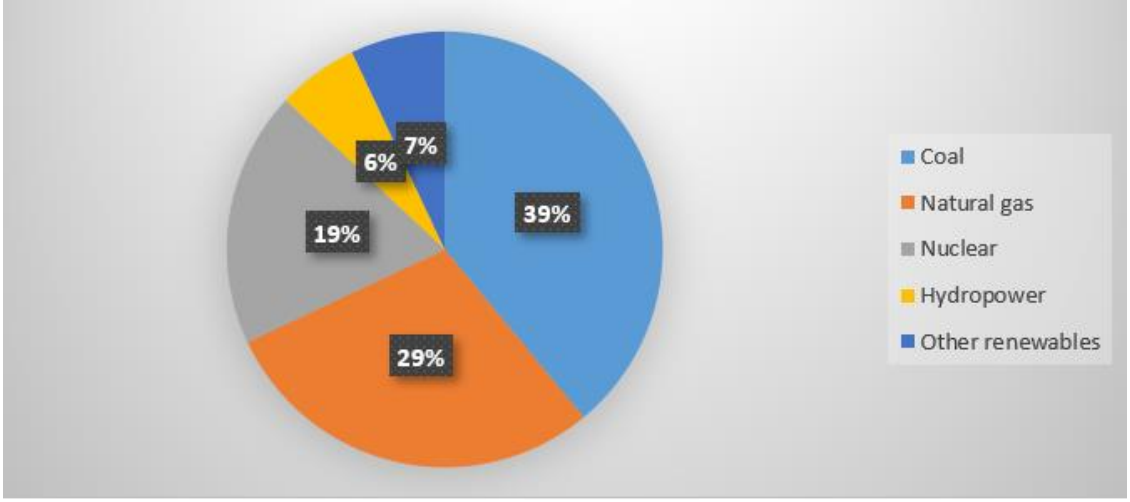


Figure 1.2 U.S. Electricity Generation by Energy Source according to U.S. Energy Information Administration.

The factors above resulted in an increased energy demand, as seen by the yearly energy consumption of buildings and the significant fluctuations in energy costs between winter and summer. Research has shown that during the summer, the energy requirements of HVAC systems in buildings and other household appliances reach unprecedented levels, depleting local energy supplies. Summer energy usage in some residential buildings increased sevenfold compared to winter. The fluctuation in energy demands across different seasons puts an additional load on electrical providers to generate power during periods of high demand (Al-Badi et al., 2011). As a result, in late 2015, the Saudi government increased the price of household energy bills by 60% due to low oil prices, putting pressure on many ordinary families to take more notice of daily living expenses.

Most of the home's energy consumption comes from the HVAC system, including other factors that are the primary influences on the energy use of major building systems. In the summer, the energy demand for HVAC systems alone can reach 50 to 70% of total home energy use, which leads to the major factor that should analysed closely (see Figure 1.3).

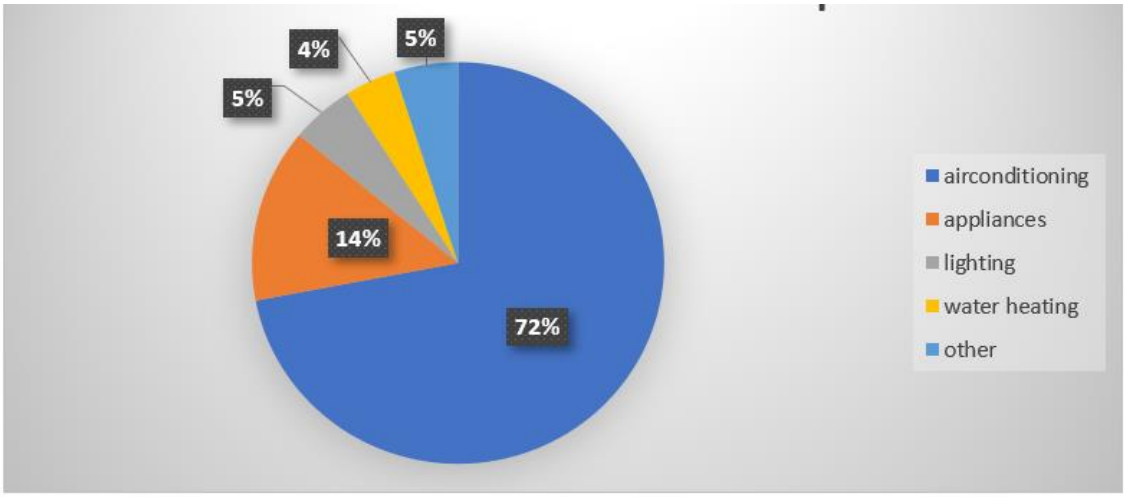


Figure 1.3 GCC Residential Power Demand Split by Building Consumption (El-Katiti, 2011).

Consequently, the GCC countries must increase their efforts to enhance their renewable energy capacity as a solution. According to the IRENA research, the GCC's power output 2019 relied on renewable energy for just 0.6% of its total generation. The GCC countries have a combined installed capacity of over 2800 MW, which accounts for just 1% of the energy needed. Compared to other dry nations in the region, which have a capacity proximity of 500 MW and contribute more than 15% to its public grid (Elrahmani et al., 2021). Moreover, to contribute to domestic energy demand and long-term environmental sustainability, the GCC countries must immediately consider the benefits of conserving energy consumption in buildings by promoting Net-zero-energy homes (NZEHs) for the regional residential market. NZEHs can be a feasible solution to reduce dependence on fossil fuels for energy production by promoting sustainable and renewable approaches in the residential sector, which can ease the pressure on the ordinary local electricity grid.

1.2- Overview of Domestic Building Distribution

Economic, environmental, social, and cultural criteria significantly influence construction methods in Saudi Arabia and other Gulf Cooperation Council countries. Consequently, building methodology modifications occur when any of these factors undergo changes. Before the 1970s, the construction industry used passive design principles in home design and building operations since they depended on local materials and climatic conditions (Al-Hinai, 1993). The main goals were the limited supply of energy resources, inadequate access to local building materials, and a shortage of financial resources to get components outside. Climate conditions significantly impact the design of structures and the use of materials globally. In the past, Gulf vernacular architecture achieved sufficient thermal comfort by using innovative concepts and systems adapted to the prevailing temperature conditions and local environment. Consequently, dwellings in coastal regions were strategically orientated towards the sea to optimise the benefits of onshore sea breezes. Further inland, further into the gulf, where the air had relatively low moisture levels, mud was used as the primary building material to provide an efficient thermal barrier against the absorption of heat throughout the summer. Over the last four decades, building techniques in the Gulf area have shifted towards more modern methodologies. Concrete is used extensively in construction, whereas local traditional materials have been progressively substituted in the building sector. The shift from traditional local materials to concrete has occurred because of concrete's improved ability to be designed in many ways, longer duration of building use, and increased ability to withstand compression. As a result, affordable mechanical air conditioning systems were developed, giving building designers more freedom to bypass natural restrictions for thermal comfort. Accordingly,

the construction of concrete block buildings did not prioritise energy efficiency during operation due to the failure to use the beneficial features of the surrounding environment in the design and layout. As stated in the 2019 report by the Kingdom of Saudi Arabia General Authority of Statistics, 89% of housing units inhabited by Saudi households are made of reinforced concrete, which is the predominant construction material. Furthermore, homes constructed using bricks or blocks constitute around 9.1% of all buildings. Traditional or stone homes have the lowest percentage among all buildings in Saudi Arabia, accounting for about 1% of the total number of buildings. (see figure 1.4).

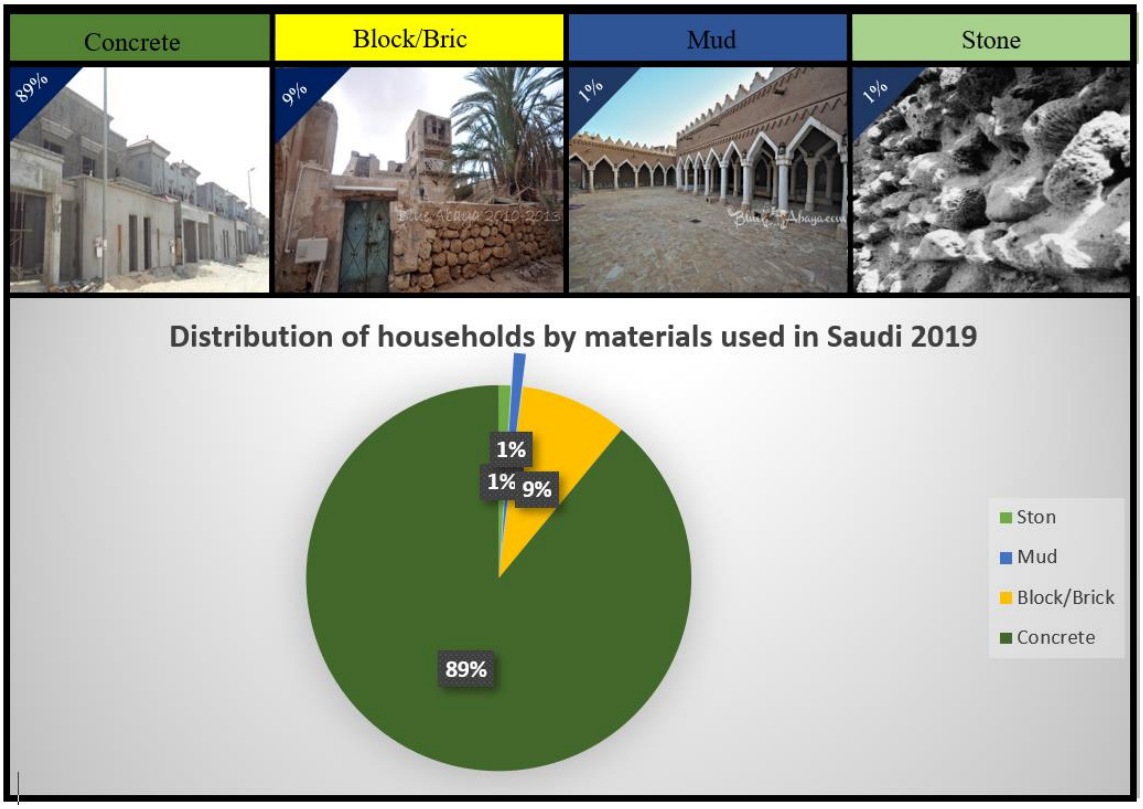


Figure 1. 4 Saudi Arabia distribution of households by building material used for house construction (Kingdom of Saudi Arabia general authority of statistics, 2019).

Regarding the type of housing, data showed that apartments were the most widespread in the Kingdom, as they acquired 43.7% of the total number of accommodations, equivalent to 1.61 million apartments, up from 1.57 million flats in 2018, followed by villas by 29.7%,

which represents 1.1 million villas. The following table shows the percentage of dwellings according to the type of residence. The Saudi General Authority for Statistics said in 2019 that the number of housing increased to 3.68 million housing units occupied by Saudi families, increasing 90.8 thousand housing compared to 2018. The number of individuals living in these housing reached 21.59 million, with an average size of the Saudi family amounting to 5.86 compared to about 5.96 in 2018. The percentage of housing units occupied by Saudi families out of the total number of dwellings was 64.85% in 2019, compared to 64.17% in 2018. The household size is understood as the result of dividing the number of individuals by the number of households. Moreover, Data issued by the General Authority for Statistics showed an increase in Saudi households' percentage of Housing in 2019, to 62.1%, compared to 60.5% in 2018 (see figure 1.5).

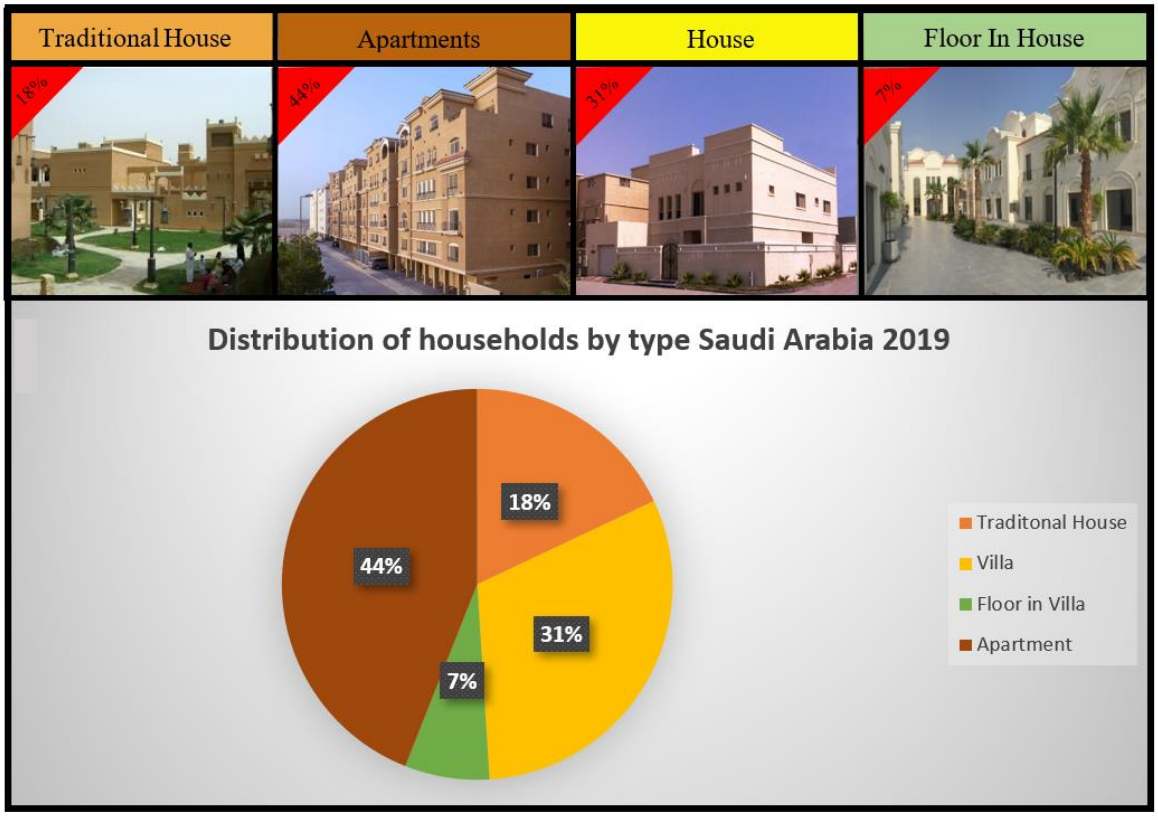


Figure 1. 5 Saudi Arabia distribution of households by building type (Kingdom of Saudi Arabia General Authority of Statistics, 2019).

The trend in Saudi Arabia is toward owning residential buildings rather than renting due to many factors, such as Government residential loans and the governmental residential buildings-supporting program which helped increase individual ownership awareness toward the housing market (GASTAT, 2019_Sakani, 2022) (see Figure 1.6).

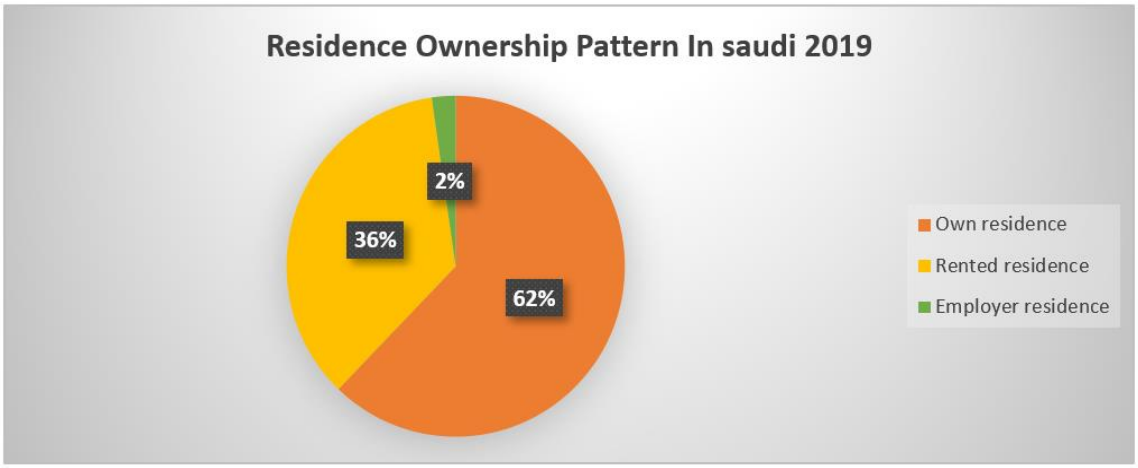


Figure 1. 6 Saudi Arabia resident ownership pattern (Kingdom of Saudi Arabia general authority of statistics, 2019).

The Ministry of Housing facilitated the journey of Saudi families to own their first home. This support is represented by the launch of a large-scale housing project, which made buying a home an easier decision than before. With the launch of Government residential loans, Saudi families can now own homes through various options and facilities, with the abundance of projects, units, and schemes offered. That kind of program seeks to provide many housing solutions for Saudis by offering various real estate units in housing projects in multiple regions in Saudi Arabia. This comes from the government's support for citizens to own their own homes and provide easy settlement approaches (Sakani, 2022).

1.3-Aim and Objectives

This research aims to investigate the technical and economic viability of NZEH on the Arabian Gulf East coast. This region was selected based on its historical–vernacular architecture, passive cooling techniques, harsh climatic conditions and cultural requirements, making constructing low-energy buildings challenging. The stated aim is achieved through the following set of specific objectives:

- Conduct an extensive literature review to learn about vernacular residential buildings' construction materials and passive cooling techniques to utilise them in this research base case. These techniques allowed ancestors to inhabit the East Coast of the Arabian Gulf's harsh climate without electricity.
- To identify the main design characteristics of a typical residential home suitable for a Saudi family and assess energy consumption trends in those buildings.
- To examine the properties and design of an NZEH and how this can be adapted to climatic conditions like those of the Arabian Gulf.
- To conduct energy modelling for the NZEH prototype, including validation and cost estimation, which is compatible with the Arabian Gulf.
- To provide general recommendations and guidelines for promoting NZEH in Saudi Arabia and the Arabian Gulf.

1.4-Research Hypothesis and Questions

The investigation hypothesises that the premise and implementation of NZEH are feasible within the Arabian Gulf East Coast's ecological and cultural context. NZEH can potentially reduce energy use while providing significant environmental and economic benefits to the Arabian Gulf's residential building industry. As a result, various research questions were asked while developing the methodology. The research questions are as follows:

RQ1-Research Question one

Which passive cooling techniques and construction materials did our ancestors use in the Arabian Gulf's harsh climate without electricity to be applied in designing the NZEH?

RQ2-Research Question Two

What elements in architectural design geometry and building envelope selection contribute to the increase in energy consumption in the Arabian Gulf region buildings?

RQ3-Research Question Three

Which energy-efficient measures are most effective for the Arabian Gulf's harsh climate and can move homes to a low energy consumption stage?

RQ4-Research Question four

To what extent is the NZEH concept feasible to apply on the East Coast of the Arabian Gulf region, and which framework can be used to reach the stage of NZE?

1.5-Research Uniqueness and Contributions

There is a lack of awareness and consideration in the field of the integration potential of passive cooling systems, extracted from the Gulf ambient environment and context, with

the architectural design strategy and geometry (Feng, 2011), (Al-khateeb and Abu-hijleh, 2019), (Shin et al, 2019), (Casini, 2020), (Eshraghi et al., 2014),(Alfaris et al., 2017),(Lan et al., 2019),(Kristiansen et al., 2019). Therefore, this research aims to develop NZEHs that integrate how our ancestors utilised passive cooling techniques (natural ventilation) in the Gulf region's harsh climate with modern renewable energy technologies. The contributions of the present research to the body of knowledge are summarised as follows:

a) Develop an innovative NZEH prototype building that enhances building envelope quality, utilising passive cooling measures and applying renewable energy to reach the NZE stage. The prototype will address architectural design, house envelope design, construction materials, and on-site renewable energy technologies. The strategies will cover active and passive measures such as building design, shading devices, heating, ventilation, air conditioning (HVAC), volumetric compositions, and wind catchers. Regarding architectural design, the proposed prototype will be evoked from the Gulf East Coast ambient environment and culture by applying some vernacular materials and techniques that focus on new construction buildings.

b) Investigate how our ancestors lived in the gulf's harsh climate by relying solely on passive cooling techniques and traditional construction materials to utilise them in creating the NZEH. The investigation aims to analyse and identify passive cooling techniques' mechanisms and functionality, including thermodynamics of air movements and the relationship between the design aspect and mechanism. Our ancestors' construction

materials will be summarised, characterised, and linked to their contribution to the efficiency of the passive cooling technique.

c) Establish Guidelines and recommendations for the NZEH application in the Gulf East Coast region, considering the harsh climate and the exceptional cultural and traditional obligations. The guidelines will suggest a feasible scenario to combine passive cooling techniques with renewable energy to reach the NZE stage. Recommendations Concerning house envelope selection and construction materials applied will be delivered at the end of the study. NZEH's design framework will also suggest approaches to utilising renewable energy strategies. Recommendations about the cost estimation payback period will be analysed to clarify the initial cost and the application feasibility from the consumer's perspective.

d) Support and enhance the development of energy efficiency programs. This research aims to produce an NZE residential building typology compatible with the Arabian Gulf energy perspective and KSA 2030 vision, which promotes utilising renewable energy and diversifying the energy source rather than depending on oil as the primary energy source.

e) Define the energy consumption trend and compare it with the local and international Energy Utilization Index (EUI) to position individual annual energy consumption on the energy international energy use per capita trend. Furthermore, distinguish standards for NZE ready stage for the Gulf East Coast context that are marked beside some developed countries' international energy use index.

f) Bridge the gap between individual energy consumption behaviour and conservation awareness by creating a more positive consumer attitude towards energy efficiency. This will be performed by highlighting the benefits of saving energy and establishing recommendations to be followed as guidelines, which will increase the public perception of energy conservation. Figure 1.7 below summarises the research objective and contribution.



Figure 1.7 Synthesis diagram illustrates Research Uniqueness and Contributions to the field of knowledge.

1.6- General Methodology

This study lays the groundwork for a detailed guideline that outlines a method for building a residential home with net zero energy (NZE) in this specific setting. The research provides accurate and quantifiable information on the methods used in constructing residential buildings that achieve Net Zero Energy (NZE) status, particularly within this specific climatic area. The organisation utilises a systematic approach at various stages to achieve its goals and objectives efficiently. Various methodologies provide favourable results that are relevant to the research investigation. To deliver research outputs of superior quality, the chosen approach must include all stages of the (NZEH) concept. This research project's data collection and analysis stages need qualitative and quantitative methodologies, including statistical analysis. The activities encompassed in this project involve doing a comprehensive examination of relevant literature, establishing detailed models of buildings, analysing data collected during site visits, and examining case studies. Hence, a combination of different research approaches was used for this inquiry (mixed methods) (for more information, see the methodology chapter). The study methodologies will be implemented in three distinct phases. The study begins with a preliminary phase focused on comprehending the described subjects inside the research domain. This involves addressing the study inquiries about our predecessors' ability to survive in the challenging environment of the Arabian Gulf area by just using passive cooling methods. Moreover, while comprehending Net Zero Energy Homes (NZEH) principles, it is crucial to emphasise certain Energy Efficiency Measures (EEM) and renewable energy methods appropriate for our specific climatic circumstances. The subsequent phase involves examining the current building methods in the area and producing a benchmark case to

serve as a reference point for (NZEH). To understand this research component, we will distribute and analyse a survey and questionnaire to residents of a public residential building. This will enable us to identify the physical and practical factors that affect home energy consumption and the tenants' opinions regarding implementing sustainable projects in the area. Additionally, there will be a visit to the site of current residential building projects in the area to see and analyse the construction methods used. In the last phase, a computer modelling programme, IESVE, will be used to create and analyse a simulation model for (NZEH) that is tailored explicitly for hot and humid regions. The computer model integrates the ideas collected and understood in the previous phases, such as passive cooling methods, EEM, and renewable energy, to determine how NZEH may be realised in the Arabian Gulf area. See Figure 1.8 for the general research methodology diagram divided into three stages to meet the main research aims and objectives. For the detailed approach, see the methodology chapter.

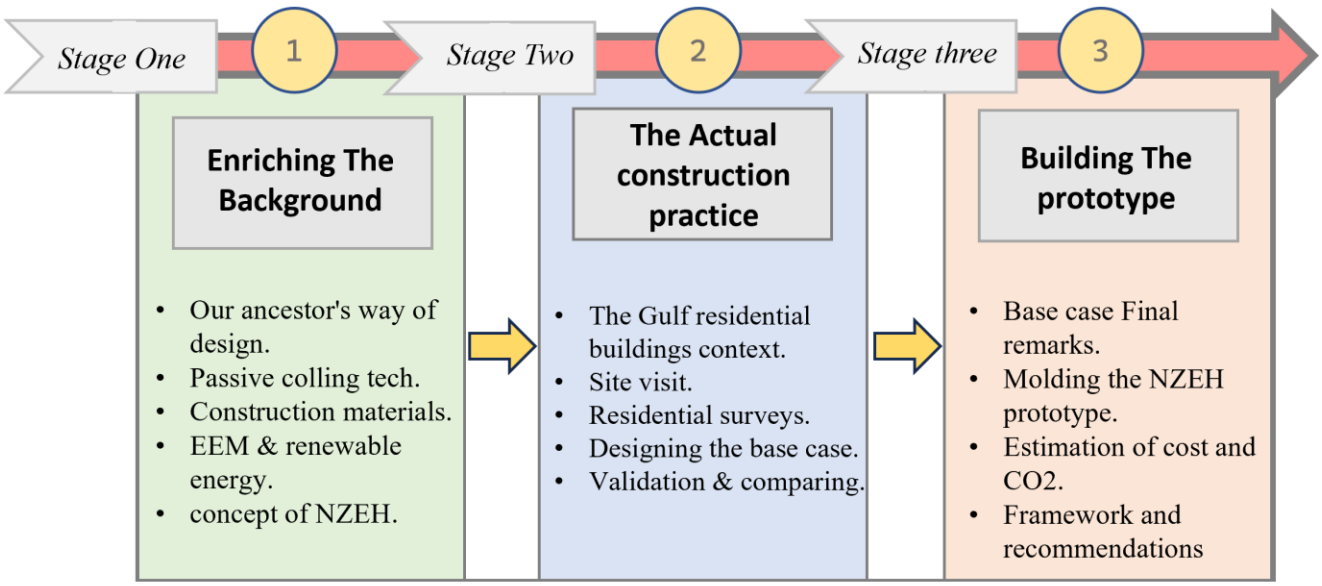


Figure 1.8 general research methodology diagram - is divided into three stages to meet the main research aims and objectives.

1.7-Structure of The Research

- **Chapter One**: - Introduction.

  This chapter briefly describes the region's energy and building residential contexts, aim, objective, hypothesis, uniqueness contributions and research general methodology.

- **Chapter Two**: - Traditional Review of Vernacular Architecture and Construction Materials in The Gulf Region.

- Review the passive cooling techniques and construction materials used by our ancestors in the Gulf region. Moreover, a summary of all the techniques has been gathered at the end of this chapter, coupled with their advantages and disadvantages to be utilized in this research NZE prototype.

- **Chapter Three:** - Energy-Efficient Measure and The Concept of Net-Zero-Energy-Homes (NZEHs) in Hot-Humid Climate

Gathers EEMs that can be utilized in hot-humid climates to apply them to the NZEH prototype. In this chapter, all investigated measures have been diagnosed to illustrate their advantages and disadvantages and judged whether utilizing them in the Arabian Gulf region climate is feasible. Moreover, it Identifies the NZEH principles and fundamentals, presenting some of the previous work done in this field of research. Moreover, this chapter has concluded that combining measures and the optimum EUI before applying renewable energy is the best method to achieve the NZE.

- **Chapter Four:** - Research methodology

Explain the method used in this research, which consists of three main stages. It focuses on building the base case for the net-zero residential building. The key factors and design

features for the Arabian Gulf base case were derived from the survey, Saudi code, site visit, and other research models. The energy-simulating tools were determined by relying upon some mandatory measures and requirements in designing the NZEH. Moreover, the base case simulation sample was validated by corresponding it with an existing home in Dammam city and other researcher models to create a sense of error regarding where this research base case stands.

- **Chapter Five:** - Residential Buildings Survey results

Identifies the main characteristics of a typical Dammam, Saudi Arabia home and emphasises the possibilities and challenges of implementing NZEHs from the resident's standpoint. At the end of this chapter, a summary was made to guide the design of the base case according to the resident's perspective.

- **Chapter six:** - Design and Conceptualization of the NZEH:

  In this chapter, the base case model will be enhanced, and the EEMs and passive cooling techniques will be applied with renewable energy's assistance to reach the NZE stage. At the end of this chapter, a conclusion will be made on whether the concept of NZEH is feasible to apply in the Arabian Gulf region.

- **Chapter seven:** - Framework, Recommendation and Conclusion

Setting the benefits and challenges of applying the concept of NZEH in the Arabian Gulf region. Moreover, the research questions will be answered, and final recommendations will be given to the government, homeowners and architects. Furthermore, this research will illustrate a finding framework and remarks. At the end of this research, future work points are aimed at the researcher and designer.

CHAPTER 2

Review of Vernacular Architecture and Construction Materials in The Gulf Region.

2.1- Introduction

In this harsh climate region, our ancestors have had a critical issue coping with living in this environment. Nevertheless, they have adapted to challenging conditions by utilizing techniques extracted from their ambient environment. Those techniques (passive approaches) interact in harmony with nature rather than conflict with it, which results in moving the Indore environment to reach the thermal comfort stage without the need for any artificial source of energy (Khalili & Amindeldar 2014). The passive design responds to the local climate and ambient environment to ensure the comfort and well-being of building users while conserving energy use. The core of designing a passive building is to utilize the best advantage of the local climate (Taleb, 2014). Both building systems and passive design parameters have been proven to be essential to reaching an NZEH goal, combined and integrated based on local climatic conditions and ambient environment (Feng, 2019). Some studies showed that passive cooling techniques could sustain the indoor temperature within the comfort range while reducing the building cooling load and energy consumption required (Bhamare, Rathod et al, 2019). In fact, our ancestors had to rely on several vernacular techniques to enhance people's comfort in the Arabian Gulf desert climates. For instance, ancient builders have had a creative way to make the building

cool and ventilated through the harsh summer by creating wind towers that make the cool air sink in and kick the hot air out by making it rise through the wind tower (Stack Effect Phenomena) then out through the wind tower opining. Those techniques that enceinte builders had, are Net-Zero, sustainable and durable in the mean of today perception for many ways: They are convenient and economical to build, Net-Zero-Energy by using only natural forces, maintenance-free and do not require any repairing parts, do not have any harm impact on nature by polluting the environment, noise, and vibration free also the materials that used in the construction are sustainable and recyclable (see figure 2.1). The original concept of those vernacular techniques was evoked from the perception of the ambient environment that our ancestors managed to interact with in a smart and creative way (Hawker, 2008). Moreover, many solutions presented on conserving energy can be applied free of cost. For instance, the buildings could be designed by incorporating passive design aspects that positively impact energy consumption without any need for active measures (Abdul Mujeebu, 2016) in the end can be concluded that the low-energy lifestyle could be easily achieved in the past with a simple passive measure without sacrificing comfort (Khalili & Amindeldar 2014).



Figure 2. 1 "Albana", the builder, is constructing a home using sets of double mud bricks in Kuwait (Kuna, *2014*).

2.2- Vernacular Passive Colling Techniques

2.2.1- Courtyards

The courtyard was utilised a long time ago in the Arabian Gulf region as one of the passive solutions. Courtyards serve as a cool private area that provides a great opportunity to hold social events. The Courtyard mechanise is considered one of the best passive solutions suitable for the harsh conditions of hot-arid regions (Hawker 2008). Cool night air settles down in the middle of the courtyard, making it serve as a cool-air lake. The cool air lake is stored in the courtyard ground and walls until the mid-morning of the following day, making it suitable to sit and enjoy the early morning hours (see figure 2.2). During the day, the courtyard can be cooler than home outside temperate, at the spaces back to the sun. On the other hand, adding trees and fountains to the space results in shading from direct solar heat gain, helps ventilate and filter dust and noise, and removes heat by convention energy. Meanwhile, the rooms that surround the courtyard get daylight and cool air from the courtyard by cross ventilation. (Khalili & Amindeldar 2014).



Figure 2. 2 Courtyard Bait al Naboodah in Al-Sharjah-UAE which is opened its doors on November 14, 1995. After its renovation and restoration, Bait Al Naboodah was reopened again on April 08, 2018 (Source: - Sharjah Museums Authority).

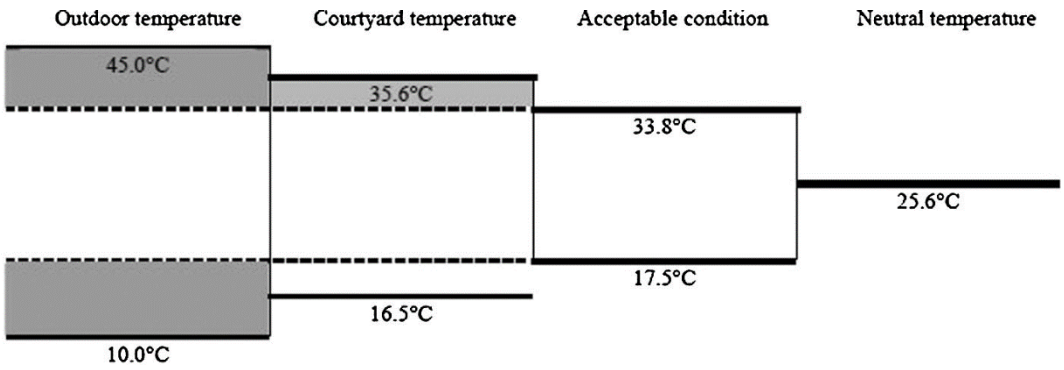


Figure 2. 3 The difference between outdoor air temperature and courtyard air temperature in Yazd, Iran (Heidari 2010).

2.2.2- Windcatcher

The "wind catcher" collects the prevailing summer wind by its opening, then cools it down and circulates it through the building. Usually, the wind tower has two ends, one rising through the roof and has many openings, and the other one reaches the end of the basement, which could "discharge opening." The upper part has four openings as a maximum, and those openings have a vertical passage used to hold a perforated wooden panel to prevent birds from coming in. Moreover, in the winter, the residents usually block the upper part opening with a sold wooden panel to keep the courtyard and rooms warm (Hawker 2008). The wind tower mechanism functions by the differentiation in the Temperature and density between the outside of the home and inside. Since the temperature outside is higher than inside, the air density outside is lower than inside, making the light air around the tower sink inside the shaft. So, the differentiation in the temperature and density makes the tower work even with the absence of wind by stack effect phenomena (Alp, 1990). On the other hand, Windcatchers inside the house are usually linked to the main spaces like a (majlas) living room and, in some cases, can serve more than one floor (Bahadori, 2006 as cited in Khalili and Amindeldar 2014).



Figure 2. 4 Esa bin Ali house in the kingdom of Bahrain has a wind tower and courtyard that surrounds by rooms (Source: - Bahrain Authority for Culture and Antiquities).

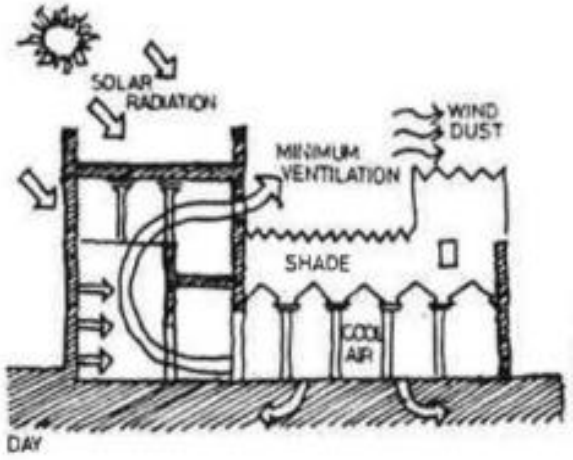


Figure 2. 5 Stack effect and air buoyancy during the day (Alp, 1991).

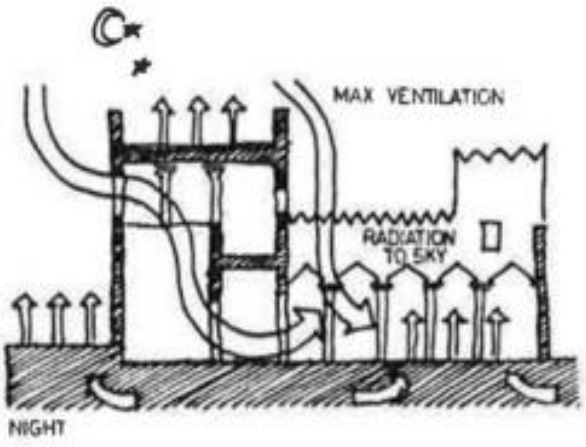


Figure 2.6 Cross ventilation through the wind tower to the courtyard at night (Alp, 1991).



Figure 2.7 A hand drawing for one of the "Al Bastakiya" houses in Dubai showing the wind tower location and mechanism (gawhary, 2015).

2.2.3- Massive walls

The Arabian Peninsula is arid; therefore, temperatures are hot during the day and cool at night. The significant temperature difference between day and night prompted the ancient builders to employ the thermal mass approach to construct their dwelling walls. Mud brick or sea stone (coral) was used to build walls, which also serve as heat reservoirs and insulators. Furthermore, during hot days, heat fluxes from the outside to the inside are slowed by the enormous walls, and during cooler nights, a portion of the heat stored in the walls is released into internal spaces via thermal mass phenomena (Alp, 1990). The mud-brick adobe walls have poor heat conductivity and great energy storage capacity, absorbing up to 80% of the outside heat and transmitting just 20% within. The enceinte builder carefully chooses the wall thickness to guarantee that the coolness collected during the summer night will give suitable temperatures for most of the following day. However, heating will not be necessary in the winter since heat is stored in walls during the day and radiated at night (Hawker 2008).



Figure 2.8 Sheikh Saeed al-Maktoum's House in Dubai was built with a massive mud brick (Adobe walls) (Hantash, 2016).

2.2.4- Wind Scoops

Wind scoops are structurally integrated horizontal wall apertures. A deep niche on the outside wall provides wind scoops that run continuously between two vertical supports. Wind scoops are often situated in the walls as openings that may cool the inside areas by cross ventilation. Bahrain, Kuwait, and the Eastern Province of Saudi Arabia still have rudimentary wind scoop uses. Variations of the same idea include recessed parapet openings along the roof terrace to ventilate the area, which is a pleasant way to spend the evening. On the other hand, wind scopes need constant maintenance since they are often obstructed by bird nests (Hawker 2008). Natural ventilation may be used with other passive methods to increase building thermal comfort and energy efficiency. Thus, by combining the wind scoop with other passive cooling measures, dwellings may easily achieve thermal comfort (Sakiyama et al, 2020).

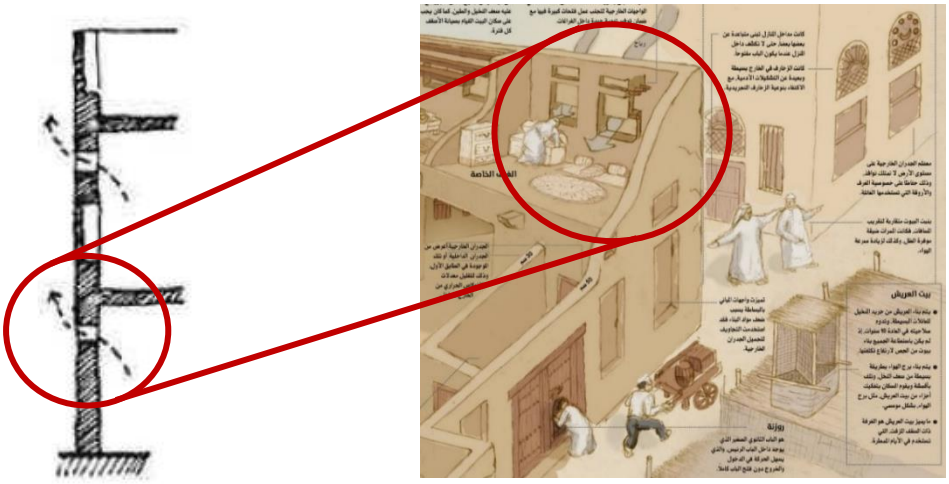


Figure 2. 9 A wind scoops in the wall helps to encourage the air circulation in rooms (Alp, 1990).

Figure 2. 10 A hand drawing for one of the “Al Bastakiya” houses in Dubai showing a wind scoops location (gawhary, 2015).

2.2.5- Basement

Underground shelters or basements are usually formed with energy conservation and thermal comfort in mind. Since the ground has a very high thermal capacity, the deeper layers' temperatures are lower than the summer ambient outdoor air temperatures. Therefore, in the summer, underground spaces have better thermal comfort and energy-saving than aboveground (M. Staniec 2011). Usually, basements are located underground with a ceiling raised by a small tolerance above the ground to allow natural light and fresh breeze to get into the space throw windows. Under the ground layers, The Earth's mass absorbs and preserves heat. Over a period, this heat is discharged to surrounding areas, including the basements. Because of Earth's high density, the swing in the Earth's temperature occurs gradually, known as 'thermal lag.' Therefore, the Earth provides a steady temperature for the basement space, even when the swing in outdoor temperature is significantly high (B. Hoyle 2011). In summer, the basement is usually occupied around noon since the underground temperature is cooler than above ground (Foruzanmehr & Vellinga, 2011 as cited in Khalili and Amindeldar2014).

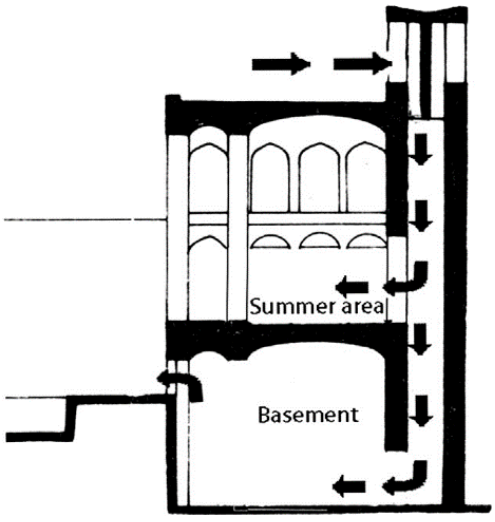


Figure 2. 11 The section shows how the basement ceiling raises above the ground to allow air circulation to cross throw basement ventilation openings (Haji-Qassemi & Karbassi, 1998).

2.2.6- Ivan

Ivan is a classic Iranian architectural method brought to the Gulf by the Banaas. Ivan's role is to provide thermal comfort conditions in neighbouring interior areas. Ivan used to be a place to sleep at night, live and relax during the day, eat supper and breakfast, host social gatherings, serve as a hallway, connect areas, and enjoy the view of the sky. In detail, Ivan is a semi-open area (Arcade) with access to the courtyard on one side. Typically, Ivan integrates into the rooms by opening doors and windows to enable cross-ventilation air to enter (Khalili and Amindeldar 2014). Ivan's measurements at Boroujerdiha residence reduced the temperature differential between interior and outdoor areas by 7◦C at 12 p.m. (Haghparast & Niroumand, 2007, as referenced in Khalili and Amindeldar 2014).

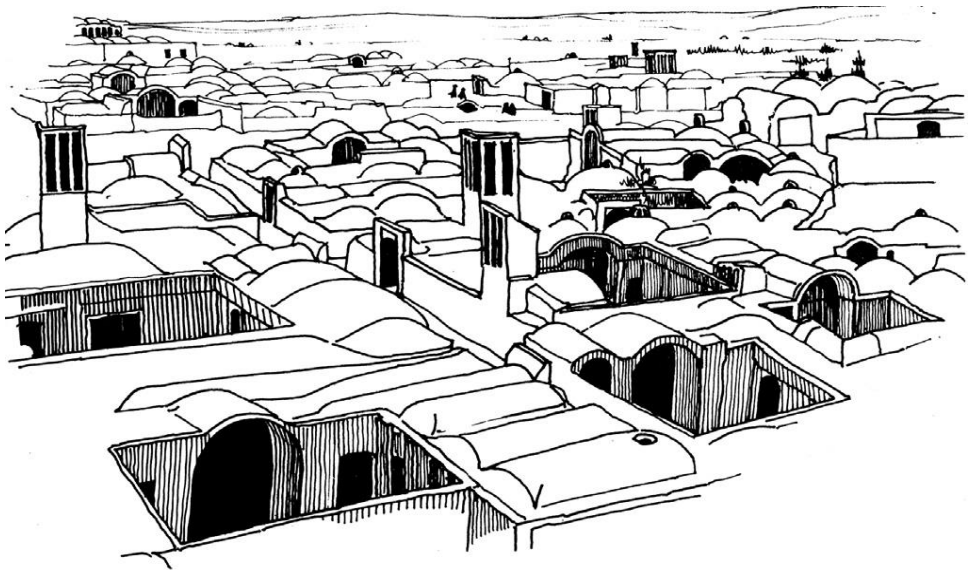


Figure 2. 12 Usually, Ivans are linking to rooms and spaces by alleyways (Tavassoli, 1982 as cited in Khalili and Amindeldar 2014).

2.3 - Vernacular Construction Materials

At the beginning of the 20th century (1901), a group of people known by the name of the master (Banna) used to build homes in the Arabian Gulf area. Usually, the (Banna) descend from a family known for its experience in construction and building (see figure 2.13). One best known, for instance, was the Al Banna family, who were originally from the Bastak district in Iran, but they relocated to the Arabian coast. Those builders could be found in the area from the North of Kuwait to the south of Dubai. However, technical knowledge was widely spread between the community, and individuals started building and maintaining their own houses. Usually, at the time, the wealthy people's houses were built using Bannas, which had several people working under them (labour), yet the lower-class people built their own houses by themselves (Hawker 2008). The materials that Al Banna used in the Arabian Gulf were from the ambient environment. The major materials are masonry, stone, plaster, wood, and palm fronds. The materials that are used in constructing the vernacular building walls are coral, stone, and mud brick. Usually, walls were decorated with a layer of gypsum plaster. Moreover, roofs were constructed using horizontal beams of palm trunks or mangrove trunks. On top of the trunks a Woven palm leaf mats and a final layer of masonry. However, during the sea trading period that was occurring at the time between the Arabian Gulf countries and India, Iran, and Germany, the Sailors imported with them some building materials that were known as imported materials (Alp, 1990).

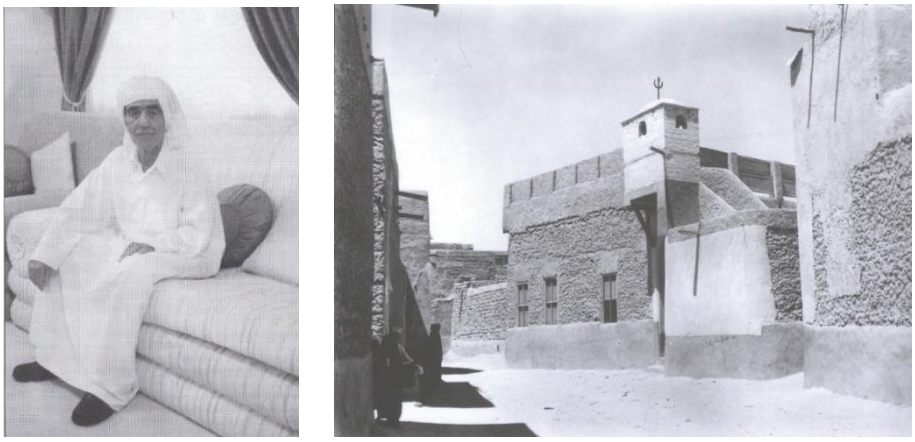


Figure 2.13 Aqil bin Mohammad Al Banna the last of seven generations of builders. Aqils ancestors migrated from Bastak in Iran to Dubai in the Arabian Gulf, and they used to build homes using mud brick (Hawker 2008).

2.3.1- Mud Brick

Since it is cheap and has a thermal insulation characteristic, mudbrick was the most common material used in constructing walls at the time. It was known between the Bannas by the name of (Libin). The Libin usually consists of a clay mixture with chaff that acts as a binding agent and soil or sand to reduce shrinkage and crack in the drying process (Hawker 2008). After casting the mud bricks in moulds, it was kept in the sun until they dried and became sold with high compressive and tensile strength (M.R. Sudhir, 2020).



Figure 2.14 This picture was captured in Kuwait at Failaka island in 1940. The picture shown Kuwaiti bannas making mud bricks then they keep it dry by the sun.(كونا, 2014).

2.3.2- Coral Stone

Usually, the stones used in building construction are coral, lime, and mountain stone. The coral-stone (sea stone) was the most expensive and preferred stone along with the cost due to its thermal characteristics. There were two types of stone houses: winter and summer stone houses. The winter stone house is usually made of stone covered with mud plaster to chink up holes that might allow the cool winter winds into the interior spaces. On the other hand, summer stone houses were made with larger holes between stones to maximise airflow and cool winds (Hawker, 2008). Airflow can lower building interior temperatures by convectively cooling the areas while contributing to good indoor air quality. The concept is based on an air exchange with the outside, which is often driven by pressure and temperature variations (Friess, 2017).

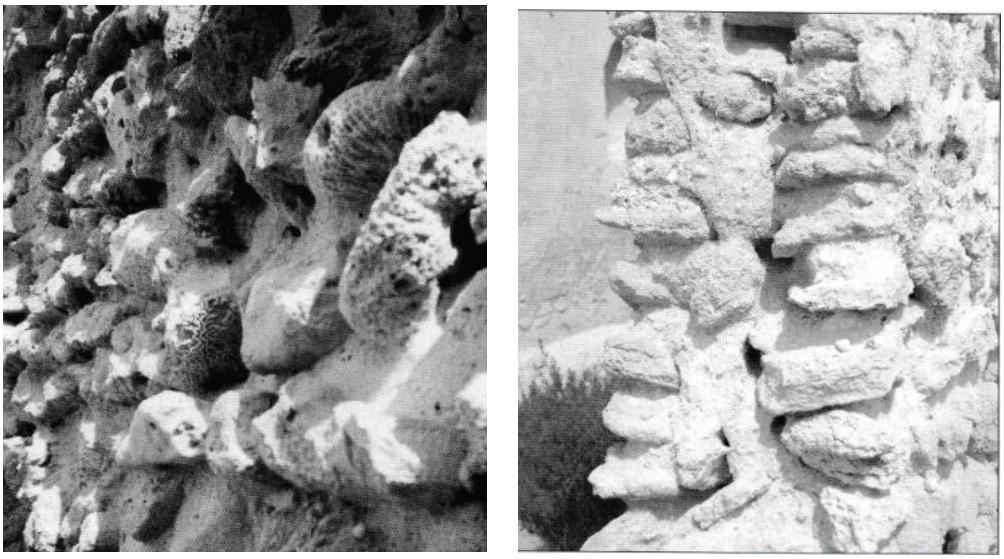


Figure 2.15 here we can see the coral stone walls. In the right picture, the wall is consisted of two coral stone layers. (Wadi hayl in Fujairah) (Hawker 2008).



Figure 2. 16 In this winter house any spaces between stones were chinked up with a mud fill (Hawker 2008).

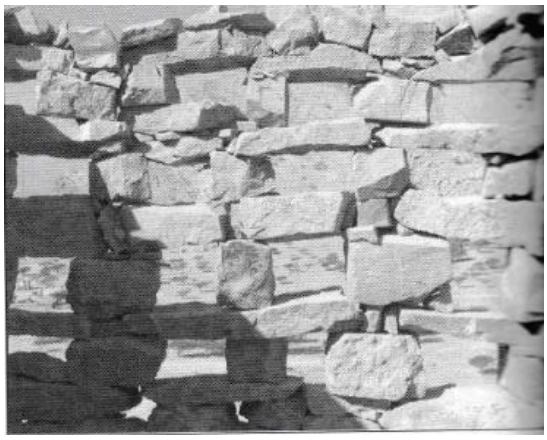


Figure 2. 13 In this summer house, spaces between stones were large to allow the cool wind air flow (Hawker 2008).

2.3.3- Plaster

At the beginning of the 19th century (1901), the plaster in the Arabian Peninsula usually came from two fundamental types. The first type was beach plaster (Juss Al-Bahar), made from mixing coral stone and shells. (Juss Al-Bahar) was uncommon because the coral was expensive and hard to get from the sea. The other common type was limestone plaster (just), and the main ingredient was alluvial limestone. This second type was more complex to make because it needed cooking for a long time to reach acceptable strength. The mixture's strength increases with an increase in the fine limestone aggregate, with a relatively small increase in compressive than sand, making the mortar strong and more durable (M. Shivakumar, 2020). On top of that, limestone plaster needs to be mixed with wood ash to have the maximum pounding between the mixture ingredients. There was a third strong type that was associated with Omani vernacular architecture. A plaster called (Sarooj) was made from red clay mixed with manure and water to make a thick paste. In fact, (Sarooj) was better than (Juss) due to its low thermal conductivity, and it keeps the interior surface cool to the touch. (Sarooj) was imported from the Persian traveler and

found in some of Dubai's traditional buildings (Hawker 2008). Altogether, Limestone and shell lime as an admixture have benefits in reducing drying shrinkage, lowering the porosity, quicker carbonation rate, and higher workability (M. Shivakumar, 2020).

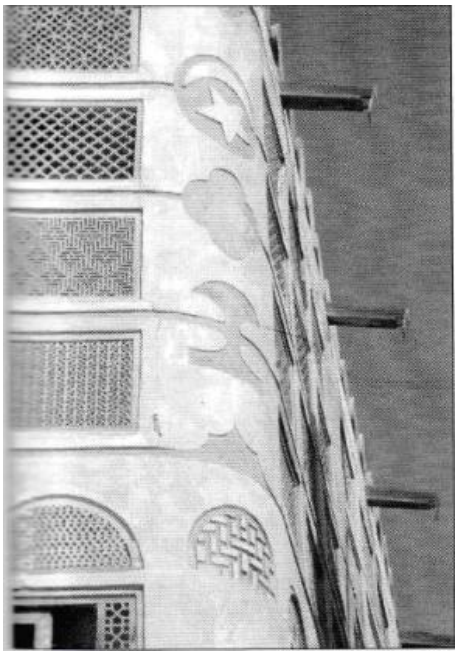


Figure 2.18 Spectacular plaster work, the Seyyadi house in Muharraq Bahrain. We can see the rounded corner plaster work and the complex window screen (Hawker 2008).

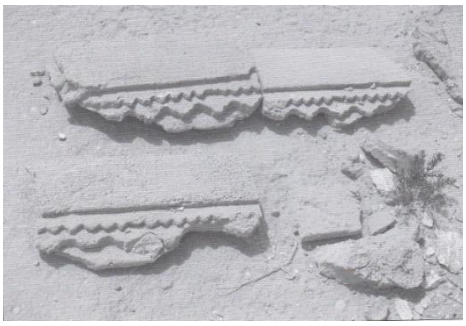


Figure 2.19 Pieces of plaster molding lie in the interior courtyard of Zaabi winter house in Jazirat Al-Hamra in UAE. The zigzag pattern was made using wooden template (Hawker 2008).

2.3.4- Palm Trunk

Date palm trees are among the oldest plants in the Palmae family. According to reports, the production of date palm fruits is expanding rapidly over the globe, demonstrating the tree's value. The number of date palm trees in Arabian Gulf nations is expected to be more than 100 million as the government promotes the palm sector and improves societal acceptability. The date palm tree may have generated fruits for over a century. It contributes to the production of raw materials for various industries and provides the national economy of many nations. (Alothman,2020). However, In the Arabian Gulf traditional buildings, we can usually see the wood element in the load-bearing beams, doors, windows, and decorations. In the beginning, individuals started building their own homes using palm trunks. It has many disadvantages. One of them is that palm trunks are subjected to a different type of Parasites and insect infestations that eat the trunk and make it very weak. Thus, individuals started to think about other wood types. Therefore, they imported wood from India, specifically from Zanzibar and Africa. For instance, Omani woodwork used Indian teak and candlewood, African teak, and a range of African and Indian rosewood. Moreover, in Kuwait and Bahrain, we can see the mangrove beams imported from India as support in the building’s roof. However, local trees in the Arabian Peninsula were used strongly in vernacular building construction. For instance, in Saudi Arabia, they utilized tamarisk trees (Athel) for doors, windows, and Islamic decoration. Furthermore, in Dubai, they used the (Al-Sidr) trees to support the roof (Hawker 2008).

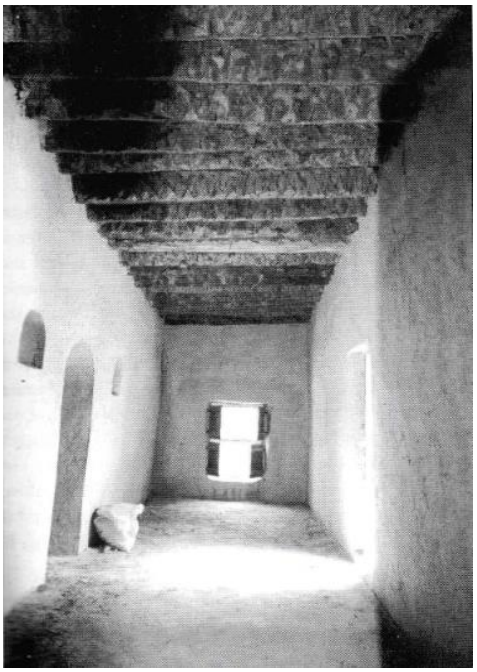


Figure 2. 20 A roof supported by palm trunks in Al-Jhra fort in Kuwait *(2014 ,كونا)*.

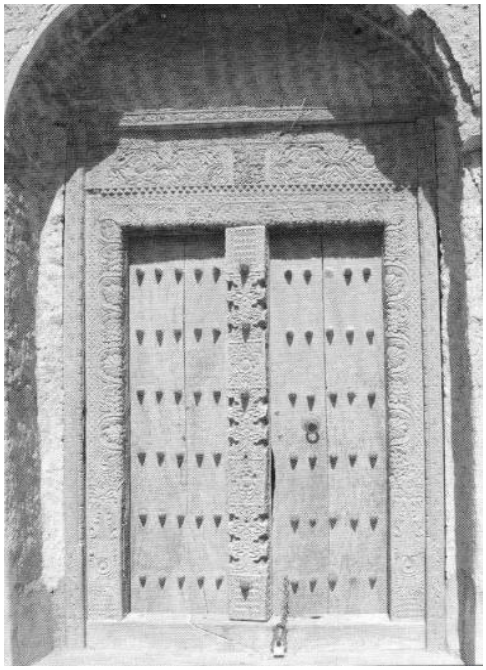


Figure 21 A large door was imported India well known for its carving industries. This door in Oman.

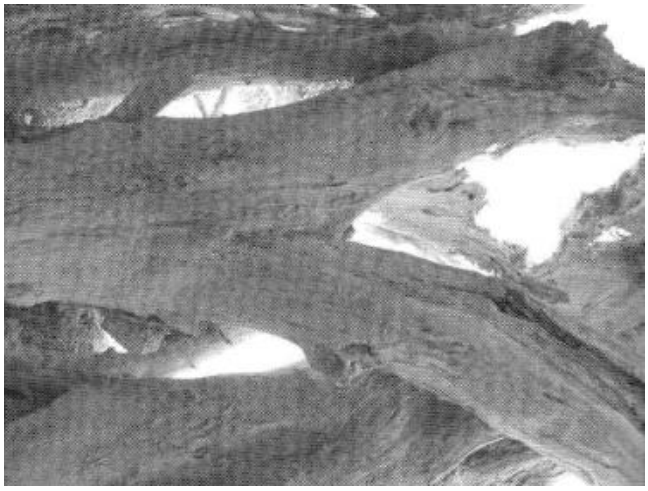


Figure 2.22 This piece of trunk a part of tree known as Al-Sidr tree usually, they use it to support the roof. The location of this trunk in Wadi sham - Ras-Alkamah -UAE. (Hawker 2008).

2.3.5- Palm Frond

The Arabian Gulf is known for the abundance of palm trees, which provide many building materials such as woven mat (Hasir), made using woven palm tree leaves. Usually, they use (Hasir) to support the roof above the mangrove beams. The palm tree's most common materials are the (Areesh), which are palm frond stems tied together to form a mat that was fixed to a palm tree trunk framework to make a standard wall. During the 19th century, wealthy individuals usually built their homes using stone, mud bricks, and coral. On the other hand, people with low incomes usually build their homes using palm fronds, which is cheaper than other building materials (Hawker 2008). In fact, Palm tree fronds were utilized in a building that was prototyped for a low-cost and energy-efficient home since they are weight and easy to construct. (Azim,1997).

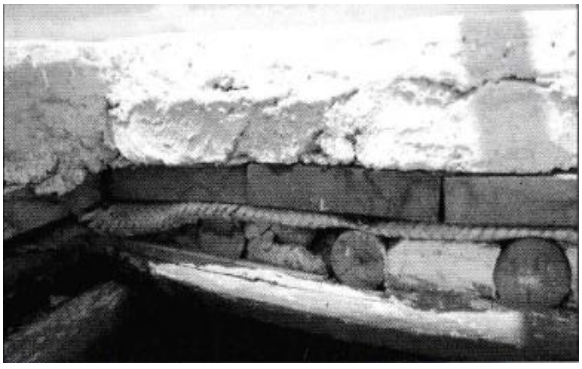


Figure 2.23 Here you can see the palm tree woven leaves (Hasir) is used in the roof construction to hold the wood plates. (Hawker 2008).

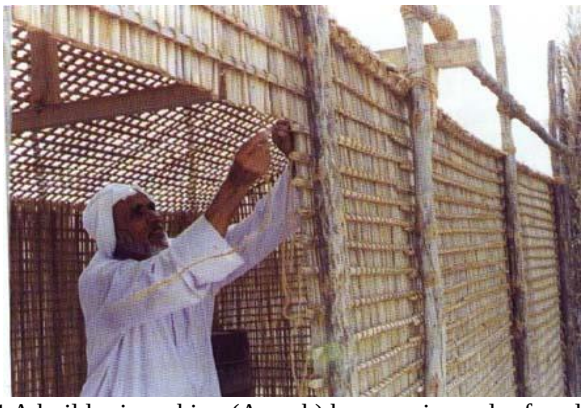


Figure 2.24 A builder is making (Areesh) house using palm frond (Ibrahim,2020).

2.4- Remarks

Like how our ancestors managed to live in the Arabian Gulf's harsh climate, we should design our homes in harmony with the ambient environment and climatic change by offering a more flexible design and a wised selection of materials that suit our environments. Integrating vernacular architectural methods into the design and construction of Net Zero Energy Homes could benefit the innovation of energy-efficient, sustainable, and culturally rich buildings. By adapting climate-responsive design, utilising local materials, and implementing ancient passive techniques, NZEH could attain enhanced energy efficiency and sustainability. Table 2.1 below reflects the study remarks on informing the research approach.

Table 2. 1 Summarises our ancestor's use of ambient environmental phenomenon and the remarks that have been reflected to inform the research methodology.

environmental phenomena		Investigations Remarks	Reflection to inform the research methodology
1	Stack Effect	stack effect is a fascinating phenomenon that operates based on the difference in temperature and density between the external and internal space areas. When the temperature outside is higher than inside, the air density outside decreases, causing the lighter air around the tower to descend into the shaft. This creates a continuous flow of air, even without wind, making the stack effect a reliable method for maintaining a comfortable indoor environment. Typically, the significant areas of the home are positioned underneath the wind catcher to take advantage of the stack effect.	Our ancestors usually utilised the stack effect phenomenon by using essential factors. There must be a container to preserve the cool air and a designated area to focus the circulated air. Also, the wind catcher's openings are constantly adjusted by wooden plates to control the air between winter and summer. Those factors must be comprehended when designing the approach for the NZEH.
2	Thermal Mass	On hot days, the giant walls reduce the transfer of heat from the outside to the inside. On colder nights, some of the heat held in the walls is released into the interior rooms via thermal mass phenomena, which triggers our actuator to use the mud-bricks adobe walls.	Thicker adobe walls can be used in traditional ways to exploit thermal mass in modern construction. The NZEH approach can use thicker walls to test the ability to save energy by increasing the wall thickness.
3	Cross Ventilation	Optimal air velocity is crucial for maintaining thermal comfort in hot and humid environments, primarily due to high humidity.	Using wind scoops is an intelligent way to make the home breathe, especially when humidity requires

		Natural air circulation is dependent on inherent propulsive forces. These powers are either the stack effect, produced by temperature variations, or the crosswind effect, generated by changes in air pressure. One example of an application is wind scoops, often positioned in walls as vents that may cool the interior spaces by cross ventilation.	high ventilation and air velocity. Also, in testing the NZEH performance, the energy simulation program must have the ability to test the heat loss that occurs from the utilization of cross-ventilation.
4	The Swing in Temp. Between Day &Night	Diurnal temperature variation often occurs in dry regions. The chilly night air descends onto the property's central courtyard, creating a refreshing oasis of coolness. The tranquil atmosphere of the lake is retained inside the courtyard's ground and walls until the late morning of the next day, creating a favourable environment for sitting and savouring the early morning hours.	The temperature swings between day and night in the Arabian Gulf region can usually reach 15°C. The NZEH design approach can be informed by creating a courtyard to store the cool night air. As in the wind catcher, it is better to preserve the cool air by creating a container such as a tree or a tent structure membrane.
5	Underground Temperature	Earth's high-density results in a slow temperature change, referred to as 'thermal lag.' Hence, the Earth maintains a consistent temperature in the basement area, regardless of the large fluctuations in external temperature. The basement is often populated around midday during the summer due to its lower temperature than the surface.	Due to Earth's stable temperature in the basement, incorporating lower area below ground level in the design approach is feasible. These places may be used at midday when the temperature is elevated. Alternatively, it is feasible to construct the courtyard below ground level.
6	Shade	Our predecessors used various methods of shadow application, such as strategically constructing the passageways between houses to maximize shade coverage. Also, shade the windows with operable wooden plates. In addition, the presence of palm palms in the courtyard provides shade and enhances the overall thermal mass of the ground and walls.	In designing the NZEH approach, it’s reasonable to include shading as a feasible EEMs. Windows can be equipped with a shading devices to minimize the solar heat gain. Also the NZEH courtyard can be shade with trees.

Below are (Tables 2.2 and 2.3) summaries of the passive cooling techniques and construction materials, which were matched with their environmental characteristics, advantages, and disadvantages and will be utilised by combining them with an NZEH in this research prototype. Moreover, from a broad perspective, Figure 2.25 shows a timeline describing the Arabian Gulf east coast construction and material development between (1800 and 1950) from using (Areech) houses to concrete blocks.

Table 2. 2 Summary of the passive cooling Techniques which were matched with their environmental characteristics.

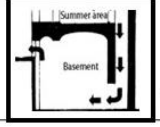
Passive cooling Techniques		Technique Description	Advantages	Disvanteges
1-Wind Tower		collect the prevailing summer wind by its opening then guide the air down and circulate it through the building.	✓ Increasing air ventilation. ✓ Works even with the absence of wind. ✓ Collecting wind from all directions. ✓ Focused on the designated desirable area.	• Large openings cumulate dust inside the area. • Tower discharger serves only one designated container.
2-Massive Wall		Using adobe walls made of mud bricks or coral stone in order to utilize the thermal mass characteristic.	✓ has high thermal capacity. ✓ Has a low heat conductivity. ✓ Absorb the heat during the day and radiate it at night.	• cannot be laid when it is raining heavily or when temperatures fall below freezing. • Massive wall thickness consumes space from the designed area.
3-Courtyard		Private cool area that opens to the sky usually it surrounded by house rooms and locate in the central of the house.	✓ helps ventilation and filters dust and noise. ✓ The ground and envelop work as a massive wall. ✓ Provides rooms with daylight.	• Hard to maintain during sandstorm seasons. • During the day, must provide shading element.
4-Wind Scoop		Sunken niche on the external wall creates a wind scoops which make the air penetrates through the building rooms.	✓ Encourage air ventilation inside the room. ✓ Provide privacy more than windows. ✓ Easy to control during winter.	• Usually, the niche is blocked by bards' nests. • Doesn't provide any view. • Limited sunlight access
5- Ivan		a semi-open space (Arcade) which has access to the courtyard from one side.	✓ creating thermal comfort conditions in adjacent indoor spaces. ✓ linking the spaces and taking advantage of the sky view.	• Can't control at cold night • It's hard to control during sandstorm seasons.
6-Narrow Alleyway		Minimize the corridors width between houses in order to achieve environmental benefits.	✓ Direct the wind breeze inside the district. ✓ Provide shade for pedestrians. ✓ Maximize land use .	• Limited privacy for houses. • Maximize flood possibility. • Limited automobile accessibly.
` *7- Basement*		A Space located underground level with a ceiling raised by a minimal tolerance above the ground.	✓ Allows natural light and fresh breeze to get into the space. ✓ Underground temperature is cooler than above ground.	• Difficult to control in the flood seasons. • Its hard to construct especially near the coastal areas .

Table 2.3 summary of the construction materials matched with their own physical characteristics.

Construction materials		Technique Description	Advantages	Disvanteges
1-Mud Brick		clay mixture with a chaff which acting as a binding agent and soil or sand in order to reduce shrinkage.	✓ Affordable and cheap material. ✓ Easily manufactured and worked. ✓ Has high thermal capacity.	• labor-intensive. • low compressive strength. • Required annual maintenance.
2-Coral Stone		A sea stone that usually found near costal areas .	✓ Light weight stone easy to handle. ✓ Has a low heat conductivity. ✓ Has high thermal capacity..	• Expansive and hard to get from the sea. • Usually, it needs double layer in order to be affective.
3-Plaster		limestone plaster (Juss) and the main ingredient is the alluvial limestone which mixed with wood ash in order to have the maximum pounding.	✓ low thermal conductivity. ✓ keeps the interior surface cool to the touch. ✓ fill up any holes in the masonry structure.	• needs cooking for a long time in order to reach the acceptable strength.
4-Palm Trunk		Usually, palm trunks were used as structural beams in order to hold the roof.	✓ Affordable and cheap comparing with the mangrove beams. ✓ Light weight and easy to handle.	• subjected to deferent type of Parasites and insect infestations • Has a low compressive strength.
5- Palm Frond		Used to make (Areesh) houses that utilized as a summer house.	✓ Light weight material that suite the harsh summer. ✓ Affordable and Easy to construct.	• Needs annual maintenance. • Not preferred in heavy rain sessions.

palm frond shelters



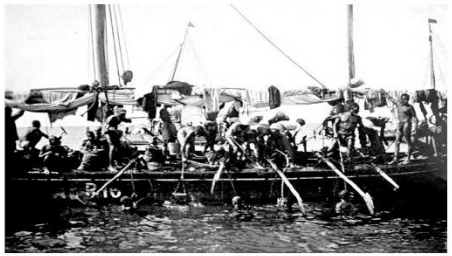
The most common product from the palm tree is the (areesh), which is a palm frond stems tied together to form a mat that is fixed to a palm tree trunk framework to make a standard wall.

Most of the buildings were built of sea stone (coral and a shell conglomerate). Coral stone was the only available stone in this coastal desert environment. Usually, to have a massive, cohesive wall, the coral stone is mixed with sand-lime mortars and rendered internally with gypsum plaster.



Coral stone houses

Pearl hunting industry



Pearl hunting was the most important career that provides a source of living for the Arabian Gulf nation. Before oil discovery, pearl hunting was the primary and vital industry between the periods of (1850-1948). The Arabian Gulf pearl was the purest globally, and the GCC countries were exported it to India.

The second significant development has been the discovery of vast reserves of oil in the 1930s. Its production brought great wealth to all countries of the region, reflecting on the construction industry. Nowadays, the majority of construction materials are coming from oil products.



The Oil discovery

1800 — **1850** — **1900** — **1950**

Tents



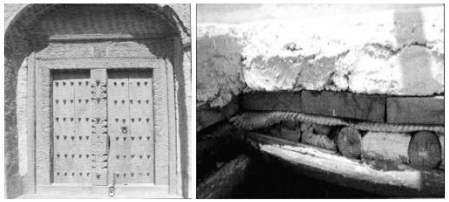
Tents were the most common shelter in the 18th century. Tents were built using animal products such as animal leathers and wools. Since individuals traveling for water resources, tents were the optimum choice for them because they are easy to install.

Since it is cheap and has a thermal insulation characteristic, the mud-brick was the most common material used in constructing walls at the time. It is known between the bannas by the name of (Libin). The Libin usually consists of a clay mixture with chaff acting as a binding agent and soil or sand to reduce shrinkage and cracking in the drying process. After casting the mud bricks in molds, it is kept in the sun until it dry and becomes sold with high strength.



Mud bricks houses

Importing materials



After the Pearl hunting industry, individuals started to think about other types of wood, so they imported wood from India, specifically from Zanzibar and Africa. For instance, Omani woodwork used Indian teak and candlewood, African teak, and rang of African and Indian rosewood. Moreover, in Kuwait and Bahrain, we can see the mangrove beams imported from India to support the building's roof.

After the second development in the Arabian Gulf, most building construction materials are coming from oil products. Moreover, houses were built using concrete blocks instead of coral stone and mud bricks. Furthermore, roofs were made using concrete slabs cast in the site instead of palm trunks.



Concrete blocks

Figure 2.25 A timeline describing the Arabian Gulf east coast construction and material development between *(1950-1800)* .

2.5- Summary

The architect or master builder (Banna) has always had many natural ways to offer the users adequate climatic comfort despite the harsh desert region conditions. The ancient builder has utilised many environmental phenomena through observation and perception by utilising the surrounding environment. Such as (Stack Effect) through wind-catchers, (Thermal Mass) in the use of massive walls, (Cross Ventilation) through Wind Scoops, (Underground Temperature) in the use of the basement, and (The Swing in Temperature Between Day and Night) through courtyards. Likewise, by understanding the material's physical characteristics, the ancient builder has decided which materials to use in summer or winter. For instance, coral stone is preferred to use in the summer because it has a low thermal conductivity due to its high porosity. Conversely, mud bricks are used in the winter to utilize their high thermal capacity. Nevertheless, locally available construction materials were widespread until the Industrial Revolution, which marked the increased use of modern techniques and standardised building materials. Modern architecture has given rise to a universal architecture that looks alike and is highly dependent on energy consumption. The lessons we are given by traditional and vernacular architecture in the harsh conditions of deserts' hot-arid-humid zones make us respect our ancestors' imagination and creativity. Nowadays, the modern builder has mimicked and evoked some modern technologies and measures by following our ancestor's ancient methods, such as insulation, glazing, finish materials, and a wide variety of shading devices to improve climatic comfort in internal and semi-internal building surroundings. Architects can attain climatic comfort by skillfully manipulating architectural design parameters and using nature abundantly.

CHAPTER 3

Energy Efficient Measures and The Concept of Net-Zero-Energy-Homes (NZEHs) in Hot-Humid Climate

3.1- Introduction

In contrast with how our ancestors interacted with their environment in harmony, as viewed in chapter two, especially in designing their shelters, most buildings in the Gulf Region are designed with no response to the local climate. Preferably, they rely on active systems to surmount the impact of uncomfortable climatic conditions, making them notable contributors to high energy consumption and carbon emissions. Therefore, much of the obligation to reduce buildings' environmental impact relies on architects, developers, and engineers. Building construction should be responsive and adaptive to local climatic conditions and ambient environment as our ancestor way of design. Architects and developers should consider utilising passive cooling techniques and energy efficiency measures in their design, which can reduce the energy needed for cooling, heating, and lighting to a figure close to zero as the building becomes an energy generator (Harris, 2002;Hawker, 2008). A thorough analysis of the improvement of energy-efficient measures in residential buildings was conducted by De Boeck et al. (2015). The study analysed 78 scholarly articles on energy efficiency in residential buildings across various regions worldwide. De Boeck et al. identified five areas of improvement for houses based on their evaluation in this study: the building's exterior, heating/cooling and ventilation

systems, glazing and shading systems, and other appliances and lights. The route to NZEH starts with improving building construction and design quality to decrease energy consumption, which depends on implementing specific energy efficiency measures that benefit all building types (Cabeza et al., 2020). This chapter will demonstrate some EEMs used in hot and humid environments and the concept of NZEHs in general.

3.2- Appropriate Energy Efficient Measures (EEMs)

Based on the principle of sustainability, the use of natural resources should be done in a manner that ensures their availability for future generations. Most choices in the building design process are made at the initial design phase. This implies that buildings should be planned and managed throughout their lifespan in a way that minimises energy use. The design phase offers the best chance to achieve high-performance structures. An excellent approach to minimising home energy consumption involves designing the building envelope with Energy Efficiency Measures (EEMs). This results in decreased energy usage for cooling purposes. An efficient building envelope may enhance the comfort and well-being of inhabitants while decreasing the energy used for cooling and lighting (Cabeza et al., 2020). This section outlines the applicable Energy Efficiency Measures (EEMs) for the Arabian Gulf region, specifically designed to address the hot and humid environment prevalent in the area.

3.2.1- Building Shape and orientation

During the early phase of an architectural project, decisions are made on the structure's core design to reduce heat gain in the summer and heat loss in the winter (Earthscan, 2011). These configurations are crucial for the geometry yearly cooling energy needs. By

strategically arranging a building form, shape, and orientation to suit the local environment, including optimising fenestration arrangement, it can significantly impact the yearly energy consumption, with potential reductions of up to 60% (Wiley & Sons, 2009). The north elevation is often shaded and does not need specific measures to prevent direct Sun exposure. Rooms with more significant internal heat generation may be positioned on the northern side of the building, where passive cooling is possible (Kristiansen et al., 2019). Exposure to sunlight causes an increase in temperature on the exterior surface, leading to a higher demand for cooling systems. A building's architectural configuration determines the extent of its exposed surface area, which directly impacts its thermal efficiency (Pacheco et al., 2012).

3.2.2- Wall and Roof Insulation

Building insulation is crucial for achieving thermal comfort for residents during cold winters and hot summers. Insulation mitigates undesired thermal transfer, hence reducing heat loss or gain and minimising the energy requirements of heating and cooling systems. Thermal insulation in walls and roofs reduces the air-conditioning system's required capacity, decreasing the annual energy consumption. Moreover, it aids in extending the duration of thermal comfort without depending on mechanical air conditioning. The roof is responsible for 60% of heat transportation, according to Soubdhan T et al. (2005). Enhanced insulation in buildings increases energy efficiency, resulting in more significant energy savings and reduced energy expenses. This has a positive impact on the environment by reducing CO2 emissions. Various insulation materials may be used to install a new roof or upgrade an old building. The roof and wall insulation is a barrier to prevent heat transfer from the outside to the building during the hot months (Aye Lu et al,

2015). According to the study, energy savings may range from 22% to 79% when the insulation thickness is between 2 and 17 cm (Bolattürk, 2006). However, having a thicker outside wall construction is not economically feasible. Still, the long-term decrease in running expenses linked to these homes offers economic and environmental benefits. The amount of heat passed through a material is governed by its level of thermal insulation. The outcome depends on several factors: density, temperature, water vapour, and porosity. As to the SBC (2018), the minimum R-values for insulation in air-conditioned houses are 5 m^2 k\ w for roofs and 2.92 m^2 k \ w for walls. The time lag is a crucial characteristic for assessing the heat storage capacity of any material. The time lag refers to the period required for the heatwave to move from the outside surface to the interior surface (Hasan H, 1998).

3.2.3- Window Shading and Glazing Type

The design of the external windows, particularly the glass, is a crucial aspect that designers prioritise when creating Net Zero Energy Homes (NZEHs) in hot regions. Large windows are prevalent in contemporary households, leading to a significant heat transmission rate. Simultaneously, windows enable the entry of natural light into a building, thus reducing the reliance on artificial lighting and fulfilling some of the lighting requirements in indoor areas (Askar et al., 2001). The transfer of heat from the surrounding environment into the interior areas of a building via a window is the cause of increased energy usage. Approximately 45-60% of the cooling load in a building is caused by heat entering via windows when windows make up 20-30% of the wall area. As to the SBC (2018), the glazing on walls should not exceed 25% of the total area, the infiltration rate in windows shall not go over 1.5 L/s, and the Solar Heat Gain Coefficient (SHGC) should fall within

the range of 0.25 to 0.35. The performance of windows depends on the optical and thermal properties of the glazing, such as U-value, solar heat gain coefficient (SHGC), and visual transmittance (Lee et al, 2013). Oliveira Panão et al. researchers assert that double glazing is a very significant energy-saving solution and recommend a thickness of 6/16/6mm, based on U-values. Ultimately, the researchers deliberated on the appropriate energy consumption threshold for a nearly Zero-Energy Building. They determined that the energy demand is heavily influenced by the chosen primary energy indicator, as stated by Oliveira Panão et al. (2013), and this might vary significantly across different nations. The North, especially in the Gulf zone, provides a scattered, less intensively heated light from the sun. Alternatively, divide the south-facing windows into views equipped with solar shade to exclude excessive sunlight and daylight windows designed to direct sunlight onto the canopy. Daylight windows should be positioned at a higher level on the wall to channel light upwards and minimise glare effectively. To provide enough winter heating, it is advisable to have windows facing south and a high Solar Heat Gain Coefficient. The eastern, western, and southern facades should have responsive sun shading mechanisms. External shade components reduce the heat absorbed during the summer, decreasing the overall energy consumption of HVAC systems throughout the year (Lechner, 2014). Persson et al. (2006) assert that altering the windows' dimensions significantly influences energy consumption. Specifically, lowering the size of windows facing south and enlarging those facing north impacts energy consumption and the maximum energy load necessary to maintain a comfortable interior temperature.



Figure 3. 3 This picture was taken by the author for the Keighton Auditorium façade at the University of Nottingham on the 12 of March 2021 at 2 27pm the shading device fall to protect the window's lower part, which is considered as under-sizing in the design process.

3.2.4- Natural Ventilation

A natural ventilation approach may help solve excess moisture in hot and humid areas while also significantly reducing the HVAC system's yearly energy consumption, which is essential on the path to NZEBs (Sudhakar, 2019). High air velocity is essential for thermal comfort due to humidity in hot and humid conditions. Natural air circulation relies on natural propelling forces. These powers are either the stack effect, caused by temperature differences, or the crosswind effect, caused by changes in air pressure (Kristiansen and Wang, 2019). Wind and stack driving forces play an essential part in air circulation. Wind cross ventilation introduces air into a building by pressure variations between its inlets and exits. When the Wind reaches the building's windward face, where a high-pressure positive

region starts, this strain drives air inside and across the structure. Consequently, an unfavourable pressure zone forms on the downwind sides. This results in air transfer from the higher-pressure region to the lower-pressure area, a phenomenon known as the wind effect. The Stack effect, buoyancy-induced ventilation, results from vibrations between inside and outside air temperatures. Because warmer air has a low density owing to density layers, it rises to exit the building via high-level fenestrations. In contrast, cooler outside air, which has a greater density, replaces it through building inlets or infiltration. Stack effect phenomena are determined by the stack height and temperature differential, which impact air density and act as a driving force (Bhamare et al, 2019). Thus, combining them is a valuable approach for improving thermal comfort. It is critical to prevent any potentially harmful consequences of this combination. For example, when they push airflow in opposing directions (cabeza et al, 2020).

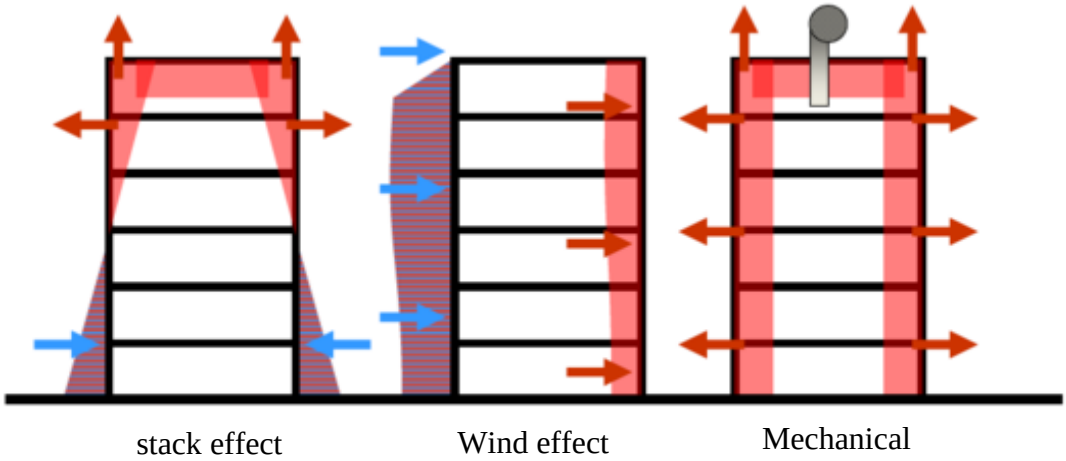


Figure 3. 4 Types of pressure that cause air infiltration/exfiltration (stack pressure, wind pressure, fan pressure) (Anas Al-Homsi et al, 2017)

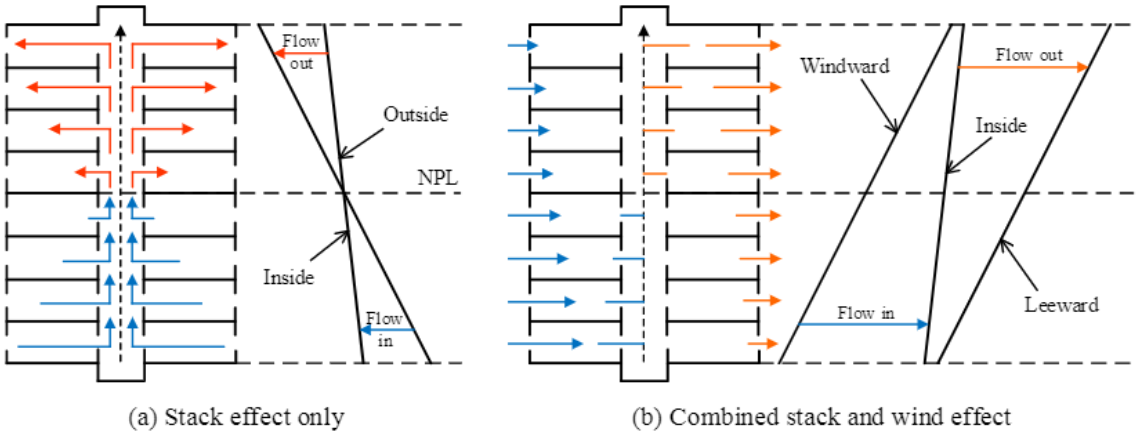


Figure 3. 5 Airflow movements and pressure distributions in Mao's study about HRR buildings. There is no restriction to vertical (floor to floor) air circulation through the building interior (Mao, 2015).

3.2.5 – Daylighting

Natural lighting is essential when designing an NZEH due to its impact on energy conservation and health advantages. In the initial design stage, reducing daylight advantages and redirecting to artificial light reliance can increase buildings' annual energy consumption (Li & Lam, 2001). Artificial lighting systems are announced to consume around 25% of the total electricity used in commercial buildings (Bleeker NC, 1993). Therefore, the designer should focus more on engaging reasonable daylighting amounts in the building and reducing reliance on artificial light. The daylight amount profoundly relies on the elevation adjustment, the fenestrations proportions and position, and the building envelope's environmental light transmission properties' (Hausladen, et al., 2008). Natural light reaches our buildings' spaces in two primary forms: direct sunlight that arrives entirely from the sun in a pure sky and diffuses light from the sky, distributed due to condensation or particles in the air. Direct sunlight generally leads to significant alterations in luminance and immediate glare. However, heat gain through windows can be

problematic since light and heat are two sides of the same coin. Spread daylight is significantly lower in heat gain than direct light. Therefore, it is favoured for thermal comfort, yet it can only be targeted over small spaces and gives low luminance. Environmental aspects such as solar altitude and sky clearness affect the illuminance, colour, brightness, and daylight amount (Szokolay, 2008). Many studies have informed the benefits of natural daylighting. A study on using the Ideal Window Area concept in combination with daylight integration to estimate the energy-saving potential. The data

K	2:1				1.5:1				1:1				1:1.5				1:2			
	N	E	S	W	N	E	S	W	N	E	S	W	N	E	S	W	N	E	S	W
0.60	41.0	25.8	22.4	17.2	41.0	24.2	23.5	12.5	27.1	27.1	17.9	11.9	26.9	29.4	16.0	10.9	28.3	24.5	17.3	10.8
0.80	43.3	27.7	23.3	15.6	44.0	29.8	22.4	16.5	30.5	29.3	21.2	10.7	29.6	29.6	16.0	11.3	30.7	23.9	16.0	10.9
1.00	41.6	28.2	25.1	16.8	42.7	29.2	23.3	15.9	33.3	28.9	19.3	11.9	31.6	28.9	16.3	12.9	32.2	24.8	15.0	12.0
1.25	43.7	25.1	22.0	15.3	42.4	29.2	21.6	14.0	35.3	27.8	19.2	13.5	33.2	28.5	16.6	12.5	33.0	25.0	16.7	11.2
1.50	43.9	25.1	22.1	16.1	43.5	26.6	19.7	14.1	37.1	27.7	18.4	13.9	35.3	28.0	17.1	12.6	33.0	24.3	16.1	11.1
2.00	43.2	25.0	20.0	16.1	41.4	28.3	19.1	14.8	37.0	25.4	26.5	13.3	33.6	26.2	16.8	13.2	30.9	23.5	15.0	10.9
2.50	40.9	23.6	18.2	15.7	38.0	26.1	17.0	13.8	36.1	24.1	16.7	13.3	32.3	24.7	15.6	11.4	28.0	22.3	14.1	11.5
3.00	39.0	22.3	15.9	14.1	35.4	24.7	15.4	12.6	34.1	22.5	15.7	12.2	29.5	22.8	15.1	7.8	26.3	21.4	14.0	11.0
4.00	35.6	20.7	14.2	13.2	31.9	23.5	13.6	11.4	29.9	21.4	14.1	12.6	26.0	20.9	15.1	11.8	22.5	19.2	13.3	10.9
5.00	31.8	19.1	13.9	11.9	28.6	22.3	12.2	12.2	26.8	19.7	13.7	12.4	24.0	18.7	14.5	11.5	20.5	16.8	12.4	10.8

Figure 3. 6 Potential for energy savings (%) on artificial lighting when using the Ideal Window Area concept combined with an outdoor illuminance of 5000 lux (Ghisi et al, 2005).

demonstrates that smaller rooms have reduced energy usage because of decreased solar heat gains, leading to savings on artificial lighting (Ghisi et al., 2005).

3.2.6 – Wall and Roof Reflectance

Wall coverings that can reflect solar radiation and release heat may lower the surface temperatures of building exteriors, reducing the amount of energy needed for cooling. When exposed to the surrounding air, things' solar reflectance and thermal emittance significantly impact their temperature. Solar Reflectance is the proportion of solar energy reflected by a surface, either as a numerical value ranging from 0 to 1 or as a percentage. As the value increases, the surface reflects solar rays more effectively. Thermal emittance refers to the amount of heat an object receives and releases. It is expressed as a numerical

value ranging from 0 to 1 or as a percentage. The higher the rating, the more efficiently the roof releases heat. Another indication exists that quantifies the surface's ability to withstand solar heat. For most construction uses, the thermal emittance of a surface is typically higher than 0.8-0.85, except for metallic components like aluminium shingles. The thermal emittance of a roof or wall component is primarily influenced by the characteristics of the layer when it is subjected to solar radiation (R. Paolini et al., 2017). The Solar Reflectance Index (SRI) quantifies a surface's ability to repel solar heat and is determined by the combined values of reflectivity and emittance. Standard black is characterised by a reflectance of 0.05 and an emittance of 0.90, whereas a typical white has a reflectance of 0.80 and an emittance of 0.90, resulting in a value of 100. According to Zinzi (2016), increasing the solar reflectance of the walls of a residential building in the Mediterranean climate by 0.1 may lead to energy savings of up to 2.9 kWh m-2 and a drop in interior temperature of 1.1 °C for buildings that are not air-conditioned.

3.2.7 –HVAC system efficiency

Heating, ventilation, and air conditioning (HVAC) systems are among the most energy-intensive components of buildings (Vahid Vakiloroaya et al., 2014). To measure energy efficiency, a collection of indicators must be defined, evaluated, and examined (Luis Pérez-Lombard et al., 2012). The Coefficient of Performance (COP) represents the energy efficiency of a single heat pump and is defined as the ratio of heating and electric power numbers. Similarly, at the cooling stage, the Energy Efficiency Ratio (EER) is defined as the ratio of cooling capacity to electrical power input. Climate factors influence both the COP and the EER. For example, the EER drops when the inside temperature is lower than the external temperature. HVAC system operating hours are often scheduled at seasonal

intervals. For example, during the cooling season, these circumstances account for just a few hours of usage. Similarly, the heat pump functions at half load, lowering the external air temperature. Two seasonal performance indicators have been created to assess HVAC system efficiency; they incorporate numerous test circumstances with varying cooling loads and external temperatures. The seasonal coefficient of performance (SCOP) is used during the heating stage, and the seasonal energy efficiency ratio (SEER) is used when cooling. They represent the ratio of seasonal cooling demands to seasonal power usage (KUNDOC, 2011). HVAC labelling is a widely established regulation aimed at improving HVAC system efficiency. The Saudi Standards, Metrology, and Quality Organisation (SASO) has issued new Energy Efficiency Labelling rules for electrical and electronic equipment.

Before entering the Saudi market, manufacturers and importers must ensure that their products fit the new regulations. In 2014, the Saudi Customs Authority set Saudi standard standards for energy label requirements and minimum energy efficiency constraints for air conditioners. Customs officials said the infringing air conditioners would not be imported as of that date, and the Ministry of Trade and Industry would not permit their sale (albawabah, 2013). According to the Saudi Energy Efficiency Centre, recommended air conditioners have an EER of 13 or above.

3.2.8 – Thermostat Setback.

The primary purpose of a home thermostat is to regulate the operation of domestic heating, ventilation, and air-conditioning (HVAC) systems. It emerged in the late 19th century to meet the need for a more organised and automated way to adjust indoor air temperature. A

conventional thermostat maintains an equilibrium between the current indoor temperature and a desired temperature setpoint to regulate the HVAC equipment's functioning (Ben-Nakhi, 2002). Roughly 50% of residences in the United States remain unoccupied throughout the day. Furthermore, 42% of homeowners tend to lower the heating temperature setpoint to preserve energy and decrease their electric costs while away from home (Peffer et al., 2011). In their research, Meier et al. (2011) found that most users, namely 90%, seldom changed the thermostat to establish a programme for holidays or weekdays. The Saudi electric company has proposed adjusting the temperature to a reasonable level of 25 degrees Celsius to minimise the disparity between the room and target temperatures (SEC, 2014). According to Malinick (2012), users often suggest that implementing a well-designed thermostat programme may result in significant savings of 10% to 30% in their electricity expenditures.

3.2.9– Thermal Mass (Adobe Walls)

In chapter one, it was shown that our ancestors successfully adapted to the intricate circumstances by using skills derived from their surroundings. Constructing large walls in their homes was one such strategy. The primary feature of the Adobe wall is its exceptional thermal capacity, which enables it to absorb and emit heat efficiently. During the drying process, water evaporates off the material's surface, resulting in heat loss in the form of latent heat. This causes a decrease in the surface temperature. The temperature difference between the surface and the building layers causes heat to flow from the outside towards the surface. Externally, the energy required to facilitate the drying process may be supplied by both sun intensity and the temperature difference between the surface and the surrounding environment, resulting in heat penetration towards the surface. However, the

heat conductivity of Adobe walls is an essential metric. Their moisture content significantly influences the thermal conductivity efficiency of adobe bricks. In addition, the presence of water in Adobe has latent heat effects, which alter both the material's ability to transmit heat and its capacity to store heat (Parra, 2005). Various research investigating the impact of thermal mass on decreasing building energy use and interior temperature has shown a significant effect. In their investigation, Kuczyznski and Staszczuk successfully decreased the average internal temperature during the August heatwave by enhancing the thermal mass of the two single-family homes. The temperature decreased by 2.8±0.34ºC, with the most significant decrease occurring at the day's peak, reaching 3.4ºC. The building's thermal mass's cooling effect remained consistent over the 14-day heatwave, with just slight daily fluctuations.

3.2.10 – Phase Change Materials

A hot-humid environment with regular diurnal temperatures throughout the year provides a year-round opportunity to use phase change materials (PCMs) for construction applications. Phase change materials (PCMs) may harness the latent heat received or emitted during their phase shift, allowing them to store thermal energy. This makes PCMs an energy-efficient solution. When integrated into buildings, Phase Change Materials (PCMs) can absorb surplus heat, creating a more consistent and pleasant interior temperature. Therefore, energy saving may be achieved by reducing the anticipated heating and cooling demand (Cao et al., 2019). Several researchers have investigated using phase change materials (PCMs) to improve the interior environment of buildings and reduce energy usage. By using phase change materials (PCM) on the inner surface of the building envelope, a government educational facility was retrofitted, resulting in a significant 11.7%

reduction in summer energy consumption and a notable gain of 215 hours in summer comfort, as shown in recent research conducted by Ascione et al. (2019). In addition, Sun et al. obtained an annual average energy conversion rate of up to 23.1% by incorporating microencapsulated phase change material (PCM) on the walls of the building (Sun et al., 2016). However, the fluctuation in temperature between day and night may restrict the performance and efficiency of the Phase Change Materials (PCMs) (Al-Absi et al., 2020). Thus, PCMSs must exhibit consistent fluctuations to facilitate a daily cycle of melting and freezing of PCMs (Khadiran et al., 2016). Choosing the transition temperatures meticulously is crucial to complete the whole thermal cycle. In addition, the efficacy of natural ventilation may be recognised in high thermal mass structures. Thus, integrating phase change materials (PCMs) with natural ventilation may effectively retain the overnight coolness and reduce the peak temperature the following day (Solgi et al., 2019; Kubota et al., 2009).

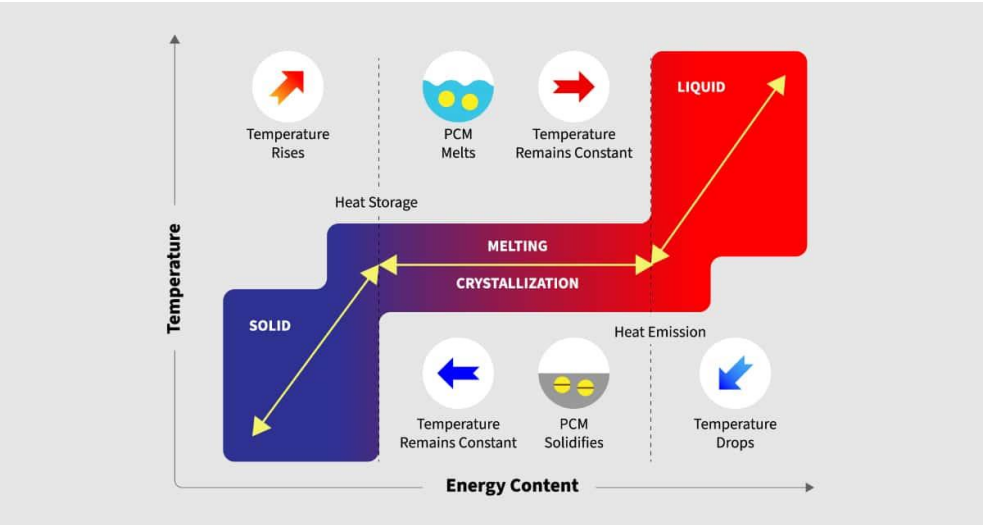


Figure 3. 7 Phase Change Materials complete melting-freezing cycle (thermtest, 2020).

3.2.11 – Green Roof

Green roofs have recently gained popularity as an effective method for incorporating vegetation into urban areas and structures. Recent technical advancements have significantly improved the flexibility and efficiency of green roof construction, enabling its integration into almost any project. Contemporary green roofs often have many levels. These components, such as plants, filters, drainage elements, root barriers, insulation, and waterproofing membranes, may be combined in green roofs to suit the individual climate and requirements (K. Vijayaraghavan, 2016; Hashemi et al., 2015). Green roofs may be classified into two categories, intense and extensive, depending on the thickness of the substrate layers. Green roofs with a thin substrate covering less than 15 cm are classified as extensive green roofs. When the substrate has a greater thickness (20–200 cm) under different circumstances, it is classified as an intense green roof. Most research on the impact of green roofs on lowering building energy consumption has shown a negligible effect compared to other energy-efficient strategies. According to Fantozzi et al., installing a green roof is not necessarily the most effective method to reduce energy consumption in a building, especially when using highly insulated clay tile as a roof finishing. The findings indicated that the highest summer HVAC system use reduction was 0.72 kWh/m2. In addition, Fantozzi et al. state that the quantity of water present in the soil of green roofs has been shown to have a substantial impact (Fantozzi et al., 2021). In their study on the evaluation and potential of green roofs and walls as a means of reducing extreme heat in Qatar, Andric et al. found that using 5 cm expanded polystyrene in combination with energy-efficient windows was significantly more effective than implementing green walls and roofs in the same climate conditions. Applying this combination resulted in a 30%

reduction in energy consumption, compared to a mere 0.3% reduction achieved by green walls and roofs (Andric et al., 2019).

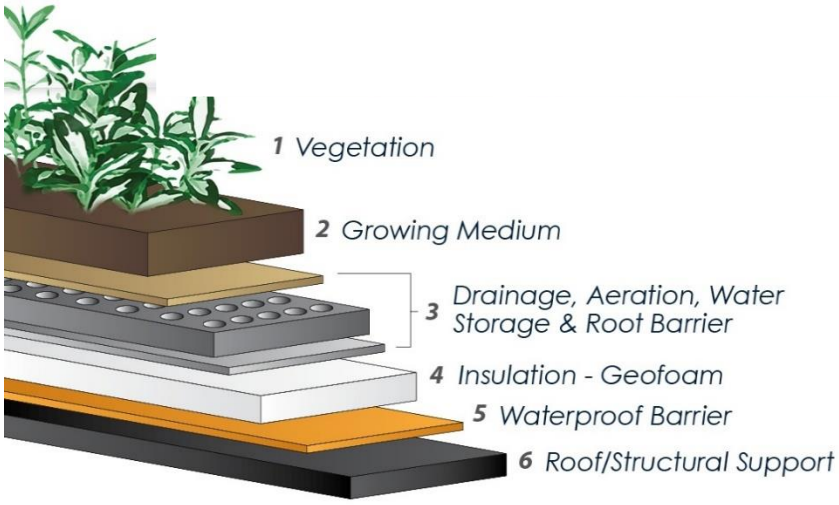


Figure 3. 8 The green roof construction and layers component according to Insulation Corporation of America.

3.3- The Design Concept of (NZEHs)

Net-zero-energy houses (NZEHs) have gained popularity in the construction industry as an appealing approach to reducing building energy usage. The concept of a self-sufficient and energy-autonomous system, famous for applications in harsh environments, has been extended to residential structures. ' zero-energy home' (ZEH) refers to residential structures that use no net energy and emit no carbon dioxide (CO2). However, there is no widely accepted definition of ZEHs in the literature. Various definitions have been proposed, each with its unique criteria. For instance, Orben V. Esbensen (1977) described an experimental zero-energy home in Denmark that was planned to be self-sufficient in terms of space heating and hot water consumption due to Denmark's steady climate. In a study of zero-energy houses in the Netherlands, Gilijamse (1995) defined a zero-energy house as one

that does not utilise fossil fuels and whose annual electricity consumption equals its annual electricity output. Khan (2004) presented a more extensive definition of the ZEH idea, stating that a 'zero energy home' is a geometry that optimally integrates existing renewable energy technologies with energy-efficient building practices. Torcellini et al. (2006) define a balanced household with significantly reduced energy demands through efficiency balance by supplying energy needs with renewable technologies. On the other hand, NZEHs can be defined based on renewable energy generation sources. This definition divides the NZEB into four types (A, B, C, D), driven by on-site or off-site renewable energy generation. This sorting system distinguishes type A as when the building generates the energy within its footprint, while B generates the energy within its site. On the other hand, C&D uses off-site renewable energy to purchase from other resources.

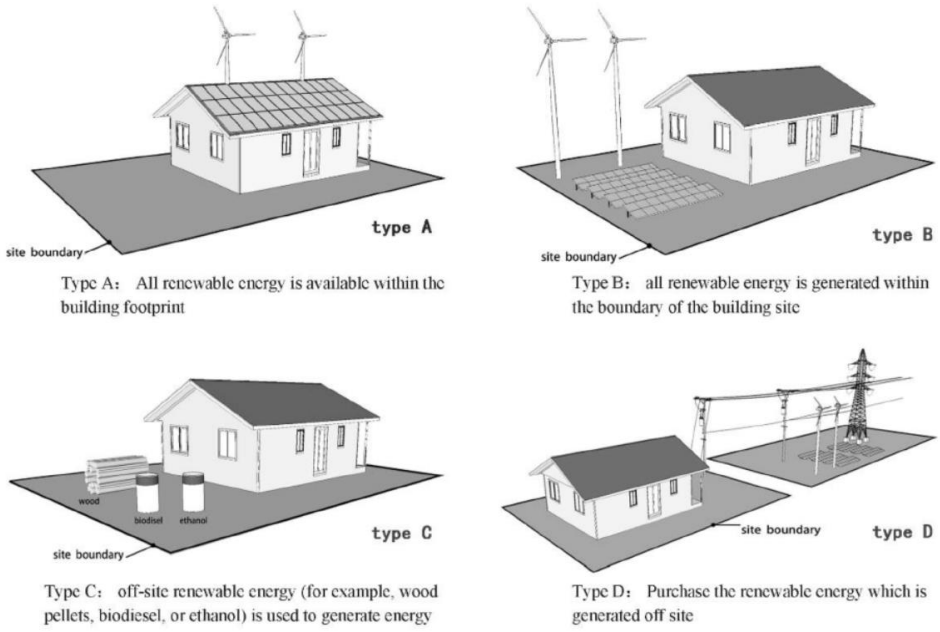


Figure 3.9 Derived from the location of renewable energy generation, four types of NZEBs are defined: A, B, C and D (Pless & Torcellini, 2010).

3.3.1- (NZEHs) Design Components

It is generally agreed that in Zero Energy Homes (ZEHs), off-site renewable energy production may be used if the on-site renewable systems are ineffective or insufficient to meet the energy needs. A crucial element of a Zero Energy Home (ZEH) is reducing energy requirements before implementing any renewable energy solutions. (see Figure 3.10).

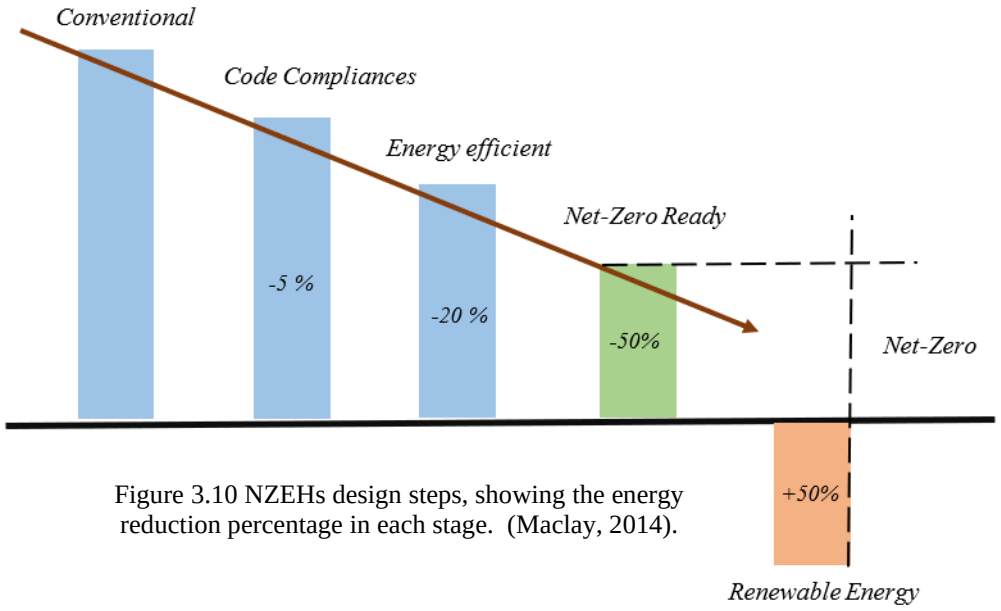


Figure 3.10 NZEHs design steps, showing the energy reduction percentage in each stage. (Maclay, 2014).

This reduction is met through coupling suitable sustainable design features and energy-efficiency measures (Pless & Torcellini, 2010). From various studies, ZEBs involve two main strategies: minimising the demand for energy use in buildings through EEMs (energy-efficient measures) and utilising RETs (renewable energy technologies) to cover the remaining energy needs. It is preferred to begin with passive energy-saving parameters before considering utilizing the active measures from a feasible aspect. These energy efficiency parameters should be selected based on cost-effectiveness, considering design factors like the house's type, size, and location. In addition, the house site should be

investigated at early design stages to determine the potential for renewable energy and to select the appropriate technologies. (sartori et al, 2012; Li, Yang, et al. 2013; Sudhakar, 2019 Cabeza et al, 2020). Moreover, the efficient design of net-zero energy buildings requires the application of some key concepts, which can include the integrated approach to energy efficiency, passive design, renewables integration, the design of the building with a realistic operation approach, and solar optimisation, which requires the optimal design of building orientation to enable the maximum capture of solar energy (Athienitis & william 2015.).

In addition to the active and passive measures, Alkhateeb (2019) has mentioned one more critical measure: user behaviour. As Picard (2020) et al. state in their study, individual consumption behaviour plays a significant role in the robustness of a ZNE home's energy performance; the annual energy simulation results of a single Californian family ZNE house showed a decrease of 23–38 percent for occupants with energy austerity behavior and an increase of 120–130 percent for occupants with energy reckless behavior. Likewise, Thomas (2013), with his prediction model that he made by gathering and analyzing the energy consumption data of 20 ZNE houses over 12 months, the research found that factors such as tenant behaviour, additional equipment, and mechanical concerns significantly influenced individual energy consumption outcomes. It is essential to conduct extensive public awareness campaigns to educate folks about the need for energy conservation. Taleb (2009) discovered a correlation between lack of information, risky behaviour, and increased energy squandered and building cooling load. Many Net Zero Energy Homes (NZEHs) have common design elements. These features include a well-insulated structure, energy-efficient lighting, advanced heating, ventilation, air conditioning (HVAC) systems,

and efficient household water heating equipment. The next step is developing a system for generating electricity in the building.

In addition, using passive cooling and heating solutions will reduce the burden on the solar panel system. For example, one design strategy is to orient the long axis of the house from east to west to optimise the exposure to the south. Additionally, shading devices on the exterior and interior may effectively shade the southern windows. Another potential strategy is to include thermal mass in the design, which can absorb heat and assist in regulating temperature variations. When developing a Net Zero Energy Home (NZEH), a key consideration is whether it is more cost-effective to reduce the house's energy use or increase on-site energy production. Anderson et al. explain the least-cost approach for determining the most economically efficient combination of energy efficiency measures and renewable energy output to reach a net-zero stage (Thomas, 2013).

3.3.2-Previous Work

There is a large body of published literature on NZEHs. Only relevant publications that can benefit this research at the design stage of a typical NZEH for the selected case study have been reviewed in this thesis. The considered publications provide a thorough basis for constructing Net Zero Energy Homes, including valuable information on optimal framework, innovative technology, economic factors, and code compliance. The reason for reviewing those publications is to help inform this research methodology and structure the wide prospective research approach. Among these publications include the following:

- Casini-2020

ReStart4Smart, a sustainable dwelling in Dubai, UAE, has achieved a net positive energy status, surpassing the UAE's highest known energy efficiency method by more than 100%. With an Energy Use Intensity (EUI) of 43.9 kWh/m2/yr., the residence is a shining example of the potential of ZEHs. The PV production system's Net Energy Use Index (n-EUI) is 161 kWh/m2/yr., meeting almost double the energy demands of the whole home under normal circumstances. Moreover, photovoltaic (PV) output exceeds the energy consumption of heating, ventilation, and air conditioning (HVAC) by more than fourfold. The analysis of official monitoring data revealed that the prototype is an energy-efficient house, producing more energy than it consumes (see Figure 3.11). This success story of the ReStart4Smart project inspires optimism about the potential of ZEHs. (Casini, 2020). Casini's research demonstrated that the UAE's surplus energy generated by residential solar panels can offset any rise in human consumption, particularly during summer when HVAC system use escalates see Figure 3.12 for the ReStart4Smart geometry design features.

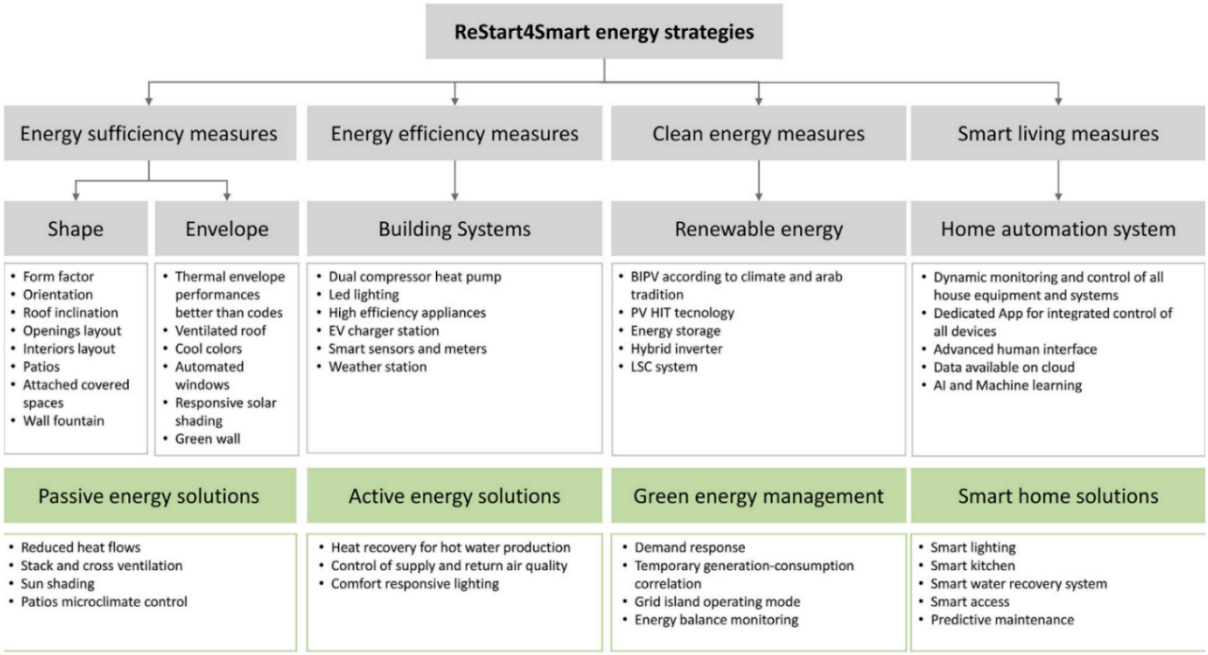


Figure 3.11 ReStart4Smart ZEH design strategies. (Casini 2020).

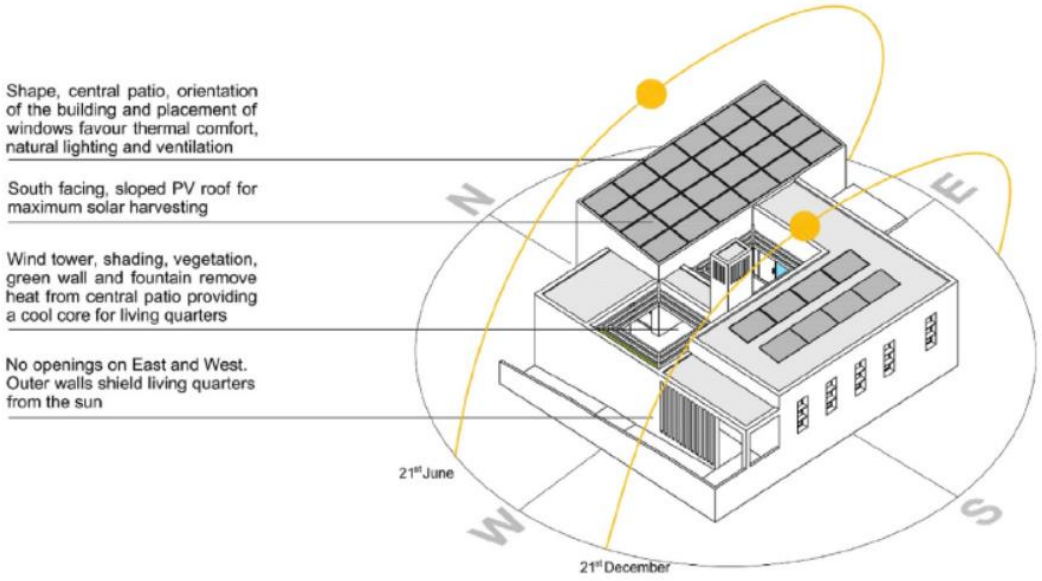


Figure 3. 12 ReStart4Smart geometry design features. (Casini 2020).

- Alkhateeb-2019

Alkhateeb conducted a study to evaluate the feasibility of converting an existing office building to achieve net-zero status. Alkhateeb utilises several passive and active methods appropriate for the UAE environment to accomplish the NZE objective, including integrating various grid-connected solar (PV) systems. He employed (IES-VE) building energy modelling software to assess the impact of all applied measures on lowering power usage to identify the best scenario before deploying PV systems (see Figure 3.13). According to Alkhateeb's research, active measures are more effective than passive ones

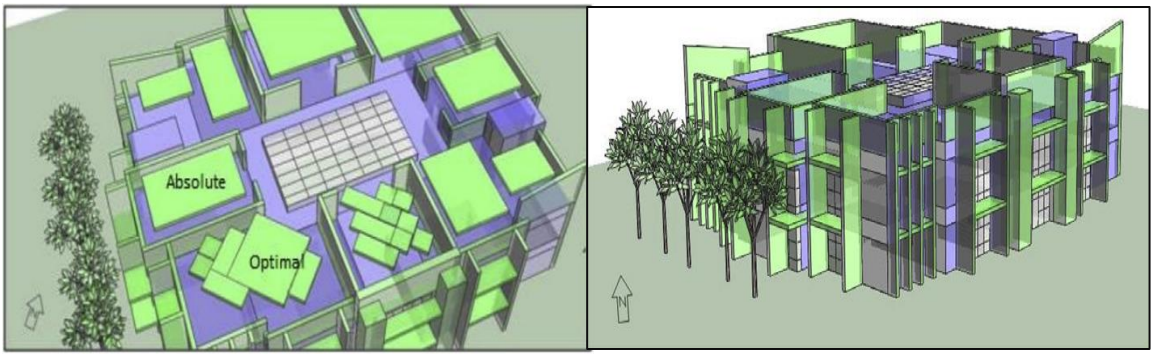


Figure 3.13 Different strategies for installing PV panels and shading elements using (IES VE ModelIT) (Alkhateeb, 2019)

in lowering energy consumption. Passive parameters cut power usage by 14.7%, while

active measures decreased demand by 63.2%. A PV system matched the lower energy consumption, resulting in a Net Zero Electricity Building (Alkhateeb, 2019). According to Alkhateeb's prototype, it is crucial to prioritise active techniques to achieve the net zero stage. However, it is essential not to overlook the passive measure while designing the study approach.

- Belpoliti et al-2019

A study managed to help the UAE utilise the passive cooling technique in a hot climate. The study was performed early, starting with the design process by selecting the orientation and construction materials and designing the passive cooling technique. The intended scheme examined and reinterpreted the initial Emirati dwelling's conventional techniques and typological design, updating them with contemporary design methods. The prototype has some new design approaches like the S/V (surface to volume) ratio is frequently adopted to evaluate the envelope's passive performance regarding heat loss. Another approach is that the house is equipped with portable partitions to allow flexibility and maximization of space, resulting in creating a (buffer zone) (see Figure 3.14), which leads to a reduction of the cooled volume and, consequently, a possible energy-saving. To help validate the geometry shape, the CFD analysis program is used mainly to analyze the environmental air-/wind-flow regarding any modeled object in a confined space, resulting in an innovative windcatcher (belpoliti et al 2019). The use of flexible space size design and spacing modification leads to a reduction in residential energy usage. The approach may be elucidated here: By altering the HVAC cooling zone, the house may decrease its cooling demand.

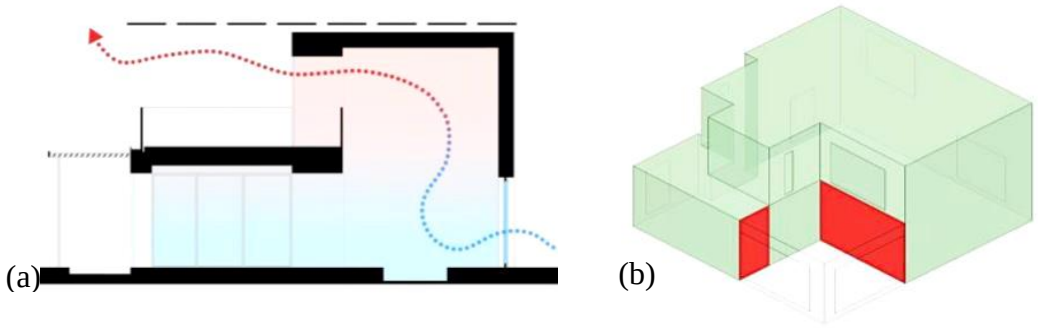


Figure 3.14 (a) The innovated windcatcher and (b) the buffer zone concept (belpoliti et al 2019)

- Taleb-2014

Recent research in the UAE sought to assess the practicality of using specific passive cooling methods to improve thermal efficiency and decrease energy use in residential buildings in hot desert climates, namely in Dubai, The United Arab Emirates. An actual case building was chosen in this inquiry, and eight passive cooling solutions were used (see Figure 3.15). The IES program served as the primary simulation tool. Using such passive cooling solutions reduced the cooling load by 9%. The yearly energy usage decreased by 23.6%. To conclude, as shown by Taleb's study, using vernacular passive cooling tactics is beneficial in reducing the building's overall cooling load and energy consumption.

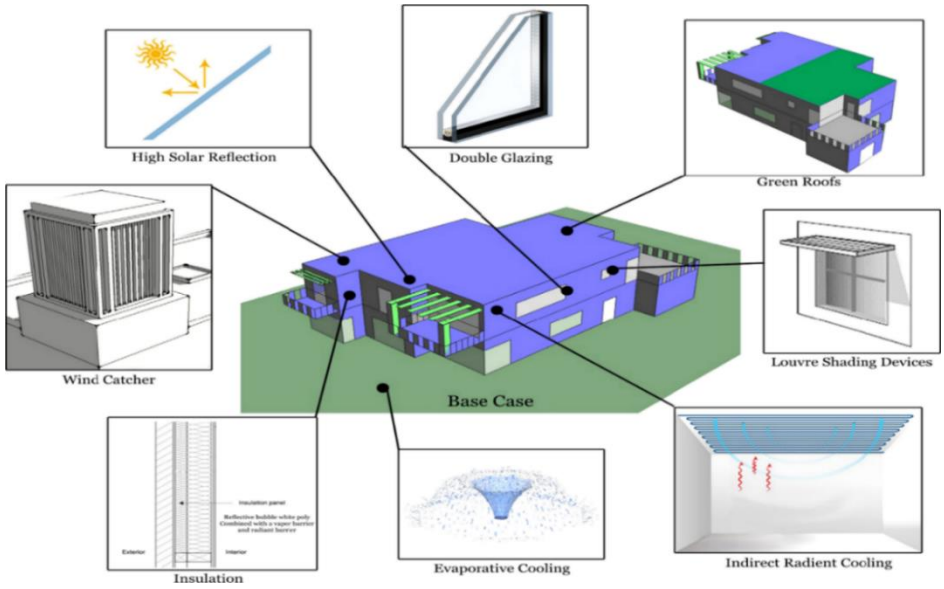


Figure 3.15approach of the adopted passive cooling design strategies (Taleb, 2014).

- Alrashed 2015

Alrashed (2015) conducted excellent research on the applicability of ZEHs in Saudi climates, comparing several ZEHs established throughout the globe under similar climatic circumstances. According to the results, Saudi virtual houses consume nearly twice as much electricity as their international counterparts due to size and type of dwelling, occupant behaviour, poor building construction energy efficiency, and domestic equipment and appliances. Airshed stated that the Saudi climate does not prevent using ZEHs in the area (see Figure 3.16). Ultimately, This research demonstrated the need to acknowledge our distinct consumption patterns in the Gulf area. The area's distinctive severe climate also amplifies cooling energy costs throughout the summer.

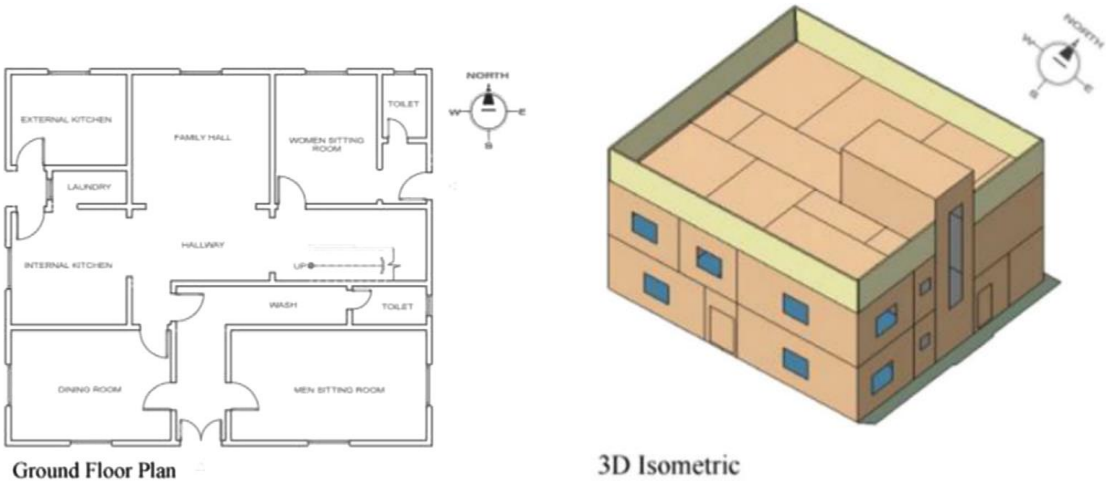


Figure 3.16 Model and floor plans for virtual house.

- Aldossary-2017

The research was able to build low-cost sustainable energy prototypes in Saudi Arabia. The three prototypes were created with the Saudi climate, culture, and occupancy needs in mind. This prototype utilizes passive cooling tactics and renewable energy technologies to produce a low-energy stage that meets international standards. Based on IES-VE analysis

data, the prototypes achieved an EUI of 98-77 KWh/m2, meeting the worldwide standard of low-energy dwellings (see Figure 3.17).

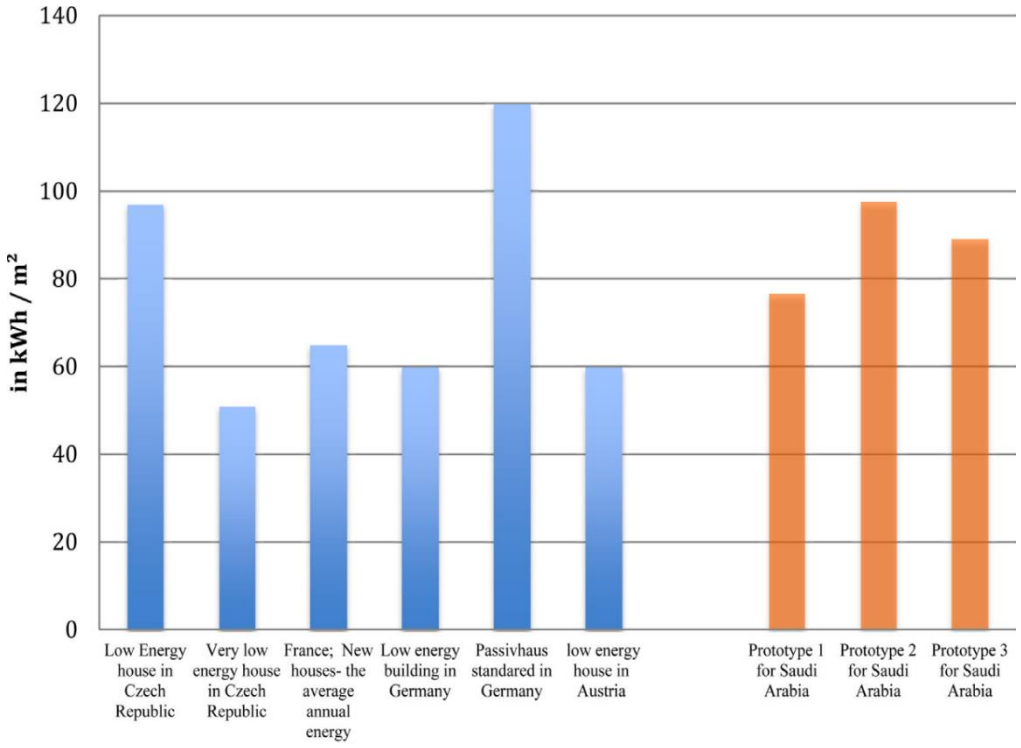


Figure 3.17 Benchmarking Energy Consumption in kWh/m2 with international standards (Aldossary, 2017)

- Alfaris, Juaidi, et al-2017

A research was undertaken in Riyadh, Saudi Arabia, focusing on smart home technologies and the impact of using renewable energy to enhance energy performance in relation to the energy benchmark. This case study shows that implementing an intelligent home system effectively enhances the house's ability to function as a net-zero energy building. The intelligent net-zero energy home consumes 78 kWh/m2 per year, whereas the baseline energy consumption index of ASHRAE 100-2015 is 107 kWh/m2/year. These advancements result in a 37% reduction in energy consumption compared to the ASHRAE standard for single-family villas (see Figure 3.18). (Alfaris, Juaidi, et al. 2017).

To conclude, home automation might be implemented in a Net Zero Energy Home (NZEH) context. According to this research, implementing this approach allows for effective management of energy use in the home, resulting in a decrease in energy consumption by up to one-third of the average energy expenditure.

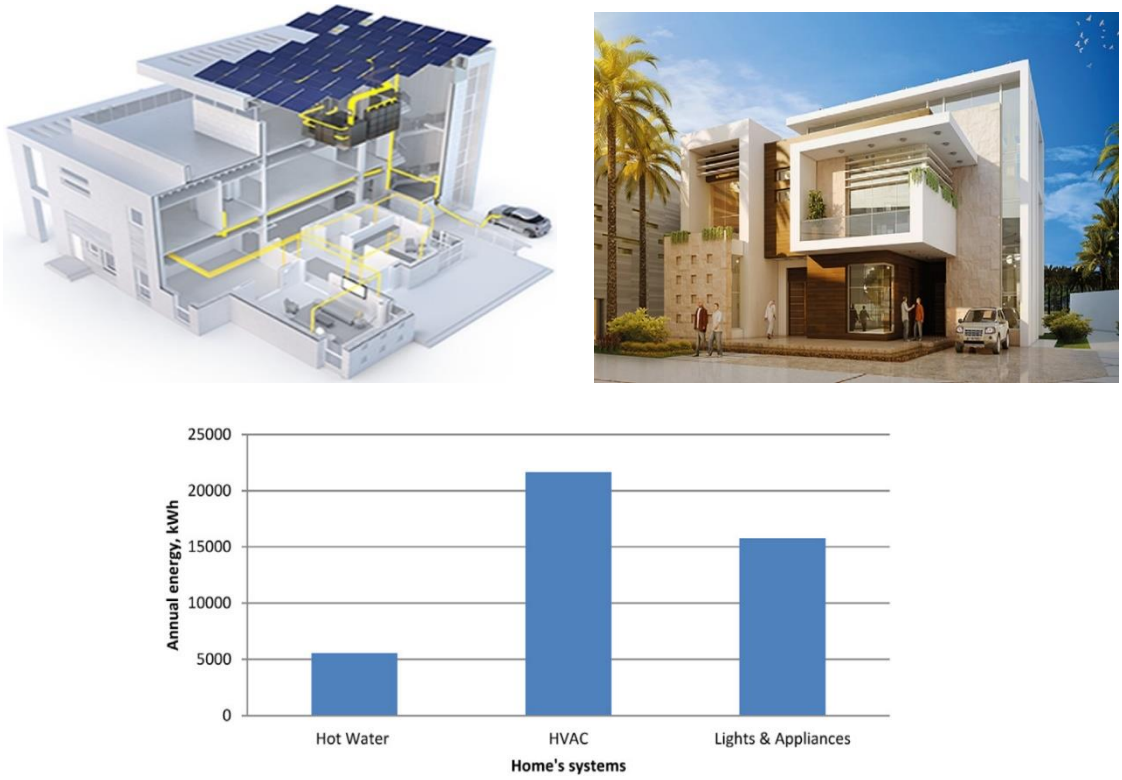


Figure 3.18 Utilizing solar energy on the roof of the studied home resulting in reducing the annual energy consumption Alfaris, Juaidi, et al. 2017.

- Lan, wood et al. -2019

A study in Singapore focused on designing a holistic approach for an NZE residential apartment building (see Figure 3.19). The design stage consists of two main phases; the design begins with Applying some considerations like passive techniques, optimising daylighting, and natural cooling time. At the same time, the other stage focuses on optimising energy performance with the application of renewable energy and life cycle

cost. The installation of solar panels for apartment buildings illustrates that with solar panels covering the roof and part of the cladding, the energy consumption of up to 19 floors can be met. In the end, while it is feasible to build a net-zero energy landed house, it is challenging to achieve net-zero energy for apartment buildings. (Lan,wood et al. 2019).

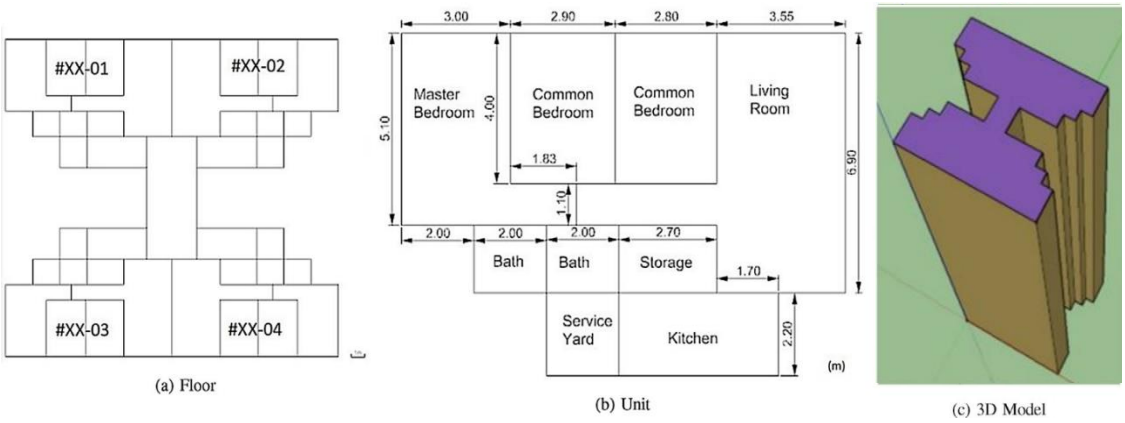


Figure 3.19 Floor plan of one floor, floor plan of one unit, and 3D model of apartment building Lan,wood et al. 2019.

Deng et al. -2011

The energy balance simulation result, employed as the primary research method of an NZEH model in Shanghai, shows that electricity generation for solar panels can meet the model's demands. Indoor comfort results show that the Shanghai model's temperature comfort can be met even under hot, humid weather. Nevertheless, humidity comfort demand needs customised energy concept design schemes (see Figure 3.120)., such as dehumidification devices (Deng et al., 2011). In the end, This research demonstrated that the Gulf region's hot and humid weather does not obstruct the implementation of the idea of Net Zero Energy Homes (NZEH). However, it is possible that the residence needs a dehumidification apparatus in order to provide optimal thermal comfort.

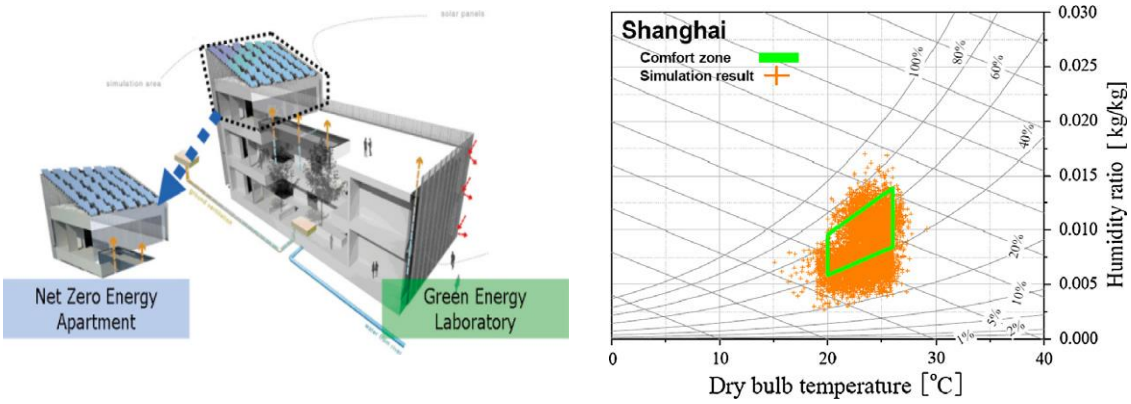


Figure 3.20 Shanghai model's comfort temperature is met even under hot-humid weather.

- Feng-2019

A comprehensive investigation examined NZEBs and their present progress in hot-humid environments. The research examined 34 instances of Net Zero Energy Buildings (NZEB) from various locations worldwide. It analysed the design methodologies, the selection of appropriate parameters, and the energy performance of these buildings. The research discovered that NZEBs in hot and humid areas often use passive design and choose features like daylighting and cross-ventilation. These strategies are combined with additional energy-efficient and renewable energy measures. Most NZEB examples exhibited an annual energy consumption below 100 kWh per square metre of floor area at the site. Furthermore, several buildings achieved a net-positive energy status (Feng, 2019). To conclude, Feng's review study on Net Zero Energy Homes (NZEHs) revealed that the majority of the homes analysed prioritised energy-efficient measures throughout the design process, resulting in a low energy consumption state of about 100 kWh/m2/year. Subsequently, renewable energy was harnessed to achieve the Net Zero Energy (NZE) level.

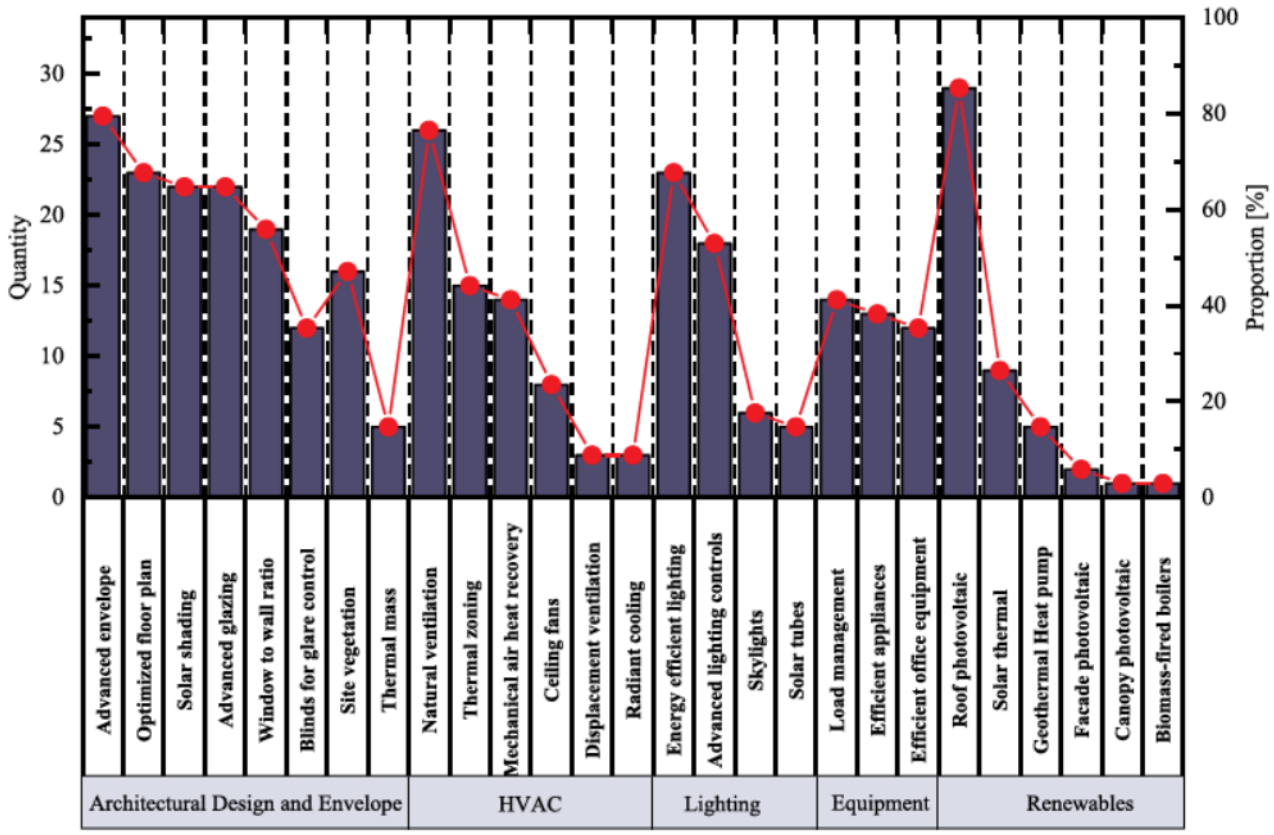


Figure 3.21Design features and building technology choices of the NZEB cases Feng, 2019.

- Rodriguez-Ubinas et al-2014

Passive design strategies play a crucial role in optimising building comfort conditions, enhancing energy efficiency, and reducing energy usage in NZEBs. A study by Ubinas et al. on Net Energy Plus Houses demonstrated the effectiveness of these strategies. The research included an analysis of the thermal characteristics of the building envelope, design parameters, ratios, and supplementary passive measures (see Figure 3.22). The results highlighted the significant impact of passive design strategies on the comfort and efficiency of homes, ultimately contributing to the achievement of the Zero Energy Buildings stage (Rodriguez-Ubinas et al., 2014).

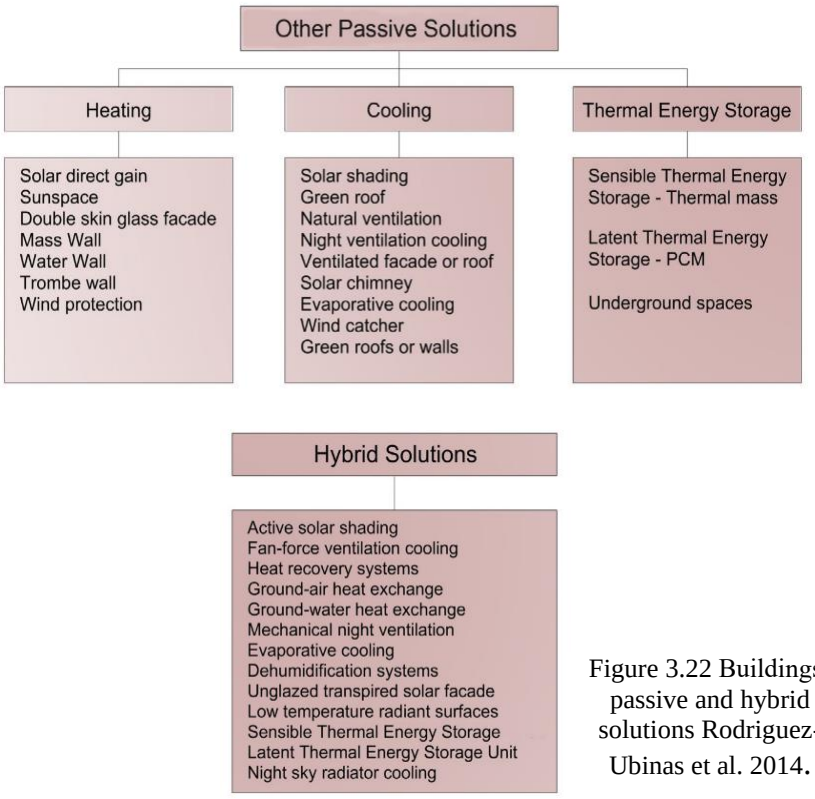


Figure 3.22 Buildings' passive and hybrid solutions Rodriguez-Ubinas et al. 2014.

- Kristiansen et al, 2019

The Kristiansen et al. study has taken steps toward achieving net zero buildings (see Figure 3.23). Kristiansen et al. technologies are focused on residential ZEBs, which are suitable for transportable modules. Kristiansen et al. conclude that Off-grid buildings make responding to what ZEB implies to the public easier. It clarifies that net-zero energy must be achieved in actual operation and include all the energy requirements (see Figure 3.24), especially plug loads. (Kristiansen et al, 2019). This research demonstrated the need to evaluate human consumption behaviour in practical settings, mainly when people consistently use their HVAC system.

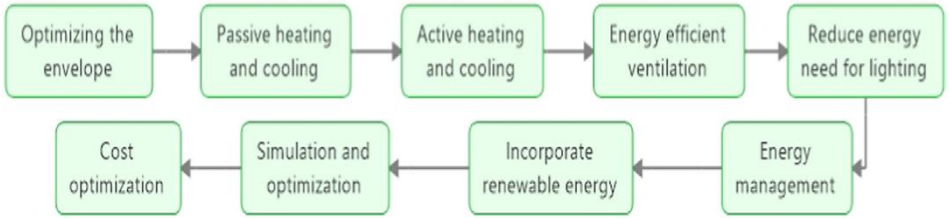


Figure 3. 23 Planning Steps Contribute towards zero energy building Kristiansen at el, 2019)

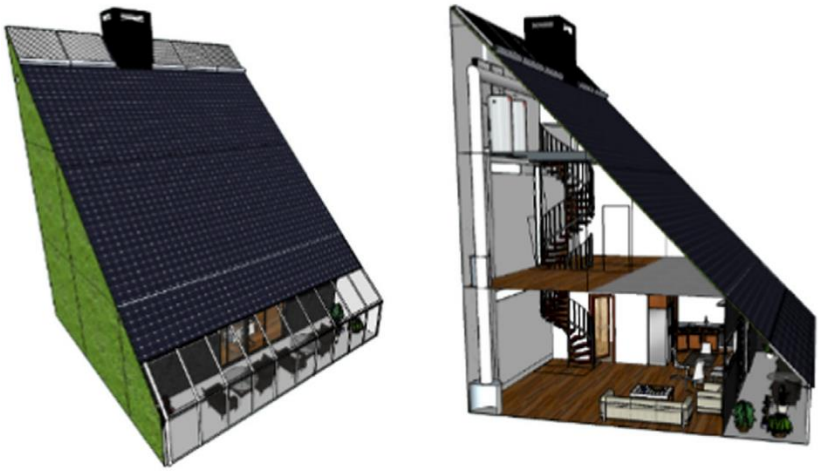


Figure 3. 24 Modular off-grid ZEB made from shipping container modules
Kristiansen et al, 2019)

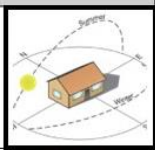
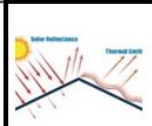
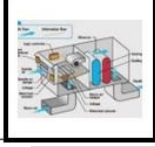
3.4-Remarks

Since the residential building industry has become a primary source of energy consumption worldwide, energy efficiency in the built environment has become a topic of interest to many architects and engineers. Energy efficiency conserves energy use and mitigates GHG emissions, influencing annual energy consumption and indoor thermal comfort. The path toward energy efficiency in buildings can be obtained through measures that vary in their ability to influence the cooling load demand. For instance, HVAC systems with a higher Energy Efficiency Ratio significantly reduce the building cooling load demand by more than 30%. On the other hand, as multiple studies have shown, green roofs are not a feasible measure to utilize in a hot climate because they have a minimal impact on reducing building cooling load, need a previous structural calculation, and must be irrigated during the year.

The choice of exterior materials, particularly glass, has a considerable impact on the building's energy demand owing to their dynamic and physical character, as well as their multi-layered roles regarding heat gain, solar gains, ventilation, and lighting. In the hot environment of the Gulf area, where solar radiation is abundant, solar heat uptake via

glazing may reach up to 85% of incoming radiation. As a result, window and glazing characteristics have a greater influence than wall measures on energy savings and thermal comfort. In terms of physical glazing characteristics, research have shown that the SHGC has a greater influence than the U-value on energy consumption and thermal comfort since it represents the amount of solar radiation that penetrates through windows. Another important aspect is window size, since heat intake from the sun rises proportionally with window area, impacting cooling demand. (see table 3.2). Summaries of the energy-efficient measures have been discussed in this chapter.

Table 3. 2 summary of energy-efficient measures that have been discussed in this chapter with some suggestions and limitations.

Energy Efficient Measures		Technique Description	Suggestions	limitations
1-Building Shape and Orientation		An Arrangements about fundamental building design (shape & orientation) At the initial stage of the architectural scheme in the meaning of minimizing summer heat gain.	✓ Rooms with higher internal gains can be located on the north side of the building. ✓ An exterior surface exposed to the sun results in heat gain, which places greater cooling systems demands.	• Can't be applied as retrofitting strategies. • can't be applied when the site location restricts the building orientation.
2-Wall and Roof Insulation		layers made by low thermal conductivity materials which reduce unwanted heat loss or gain and minimize the energy demands of heating and cooling systems.	✓ According to (SBC, 2018) R-value for insulation should not be less than 5 m^{2*} k \ w for roofs and 2.92 m^{2*} k \ w for walls. ✓ A study showed that insulation with a thickness of 2 cm could save energy up to 22% .	• Thicker external wall insulations are not financially feasible.
3-Window Shading and Glazing Type		Shielding fenestrations by vertical or horizontal elements (fins or overhangs) prevents direct solar heat gain and allows daylighting.	✓ According to (SBC, 2018) glazing should not exceed 25% from the total wall area, infiltration rate in windows should not surpass 1.5 L/s and SHGC should be between 0.25 - 0.35.	• About 45-60% of the building cooling load generates by heat gain throw windows in cases where windows cover 20–30% of the walls.
4-Natural Ventilation		Natural driving forces which are either the stack effect, due to the temperature variation, or the crosswind effect, due to the difference in air pressure .	✓ A high air velocity is required in hot and humid climates to ensure reaching the thermal comfort situation due to the humidity. ✓ Combining driven forces is a helpful strategy for better thermal comfort.	• It is vital to avoid any possible adverse effects of forces combination. • Not feasible at high outdoor temp.
5-Day lighting		On the initial design stage, utilizing the daylighting and minimizing the artificial light reliance can decrease buildings' energy consumption.	✓ Diffused daylight is considerably lower in heat gain than direct light. Thus, it is favored in thermal comfort. ✓ Rooms whose width is greater than its depth have higher daylight levels.	• Engaging more daylight in the building may result in added more heat gain.
6-Wall and Roof Reflectance		Wall coatings with high solar reflectance and thermal emittance to reduce façades exterior surface temperatures.	✓ An increase of walls solar reflectance by 0.1 can afford cooling energy savings up to 2.9 kWh m-2 and reduce the indoor temperature by 1.1 °C.	• Higher SRI values are restricted in brighter colors which put a limitation on a building surface color selection.
7- HVAC System Efficiency		Install HVAC systems with a higher Energy Efficiency Ratio (EER), which influences buildings cooling demand.	✓ According to (SEC), Air conditioners must have an energy efficiency ratio of 13 EER and above to be energy efficient. ✓ The EER increase when the outdoor temperature is lower than the outdoor.	• Unfeasible to be applied as retrofitting strategies • HVAC systems with higher EER are not financially feasible.

8- Thermostat Setback		Balancing the actual indoor temperature with an objective temperature setpoint to control the HVAC equipment's performance status results in cooling demand reduction.	✓ Users often recommend that a reasonable thermostat program bring a range of 10% to 30% reduction to their electrical energy bills . ✓ According to (SEC), its recommended to set the Thermostat to a moderate degree 25 ºC.	• Studies have reported that 90% of users seldom adjusted the thermostat to set a holiday or weekday program.
9- Thermal Mass (Adobe Walls)		The Adobe wall's main future is the high thermal capacity that allows it to store and radiate stored heat between day and night.	✓ the moisture content of adobe blocks has a significant effect on thermal conductivity efficiency. ✓ Studies indicate that structural elements with a higher thermal mass can reduce energy consumption by up to 3%.	• Works in high efficiency only when there is a swing in outdoor temperature between day and night. • Adobe walls are heavy and consume indoor space.
10 -Phase Change Materials		(PCMs) can utilize the latent heat absorbed or radiate during the materials' phase change affording a thermal energy storage capacity.	✓ The transition temperatures should be chosen carefully to guarantee the entire thermal cycle. ✓ Moreover, coupling night ventilation with PCMs application is a helpful way to enhance the freezing process.	• PCM must have proper daily variations to allow a daily absolute PCMs melting-freezing round .
11- Green Roof		A Green Roof made of layers that enhance a typical roof's insulation efficiency by controlling the heat transferal into the building.	✓ green roof cannot always be considered the best measure for reducing energy consumption in a building. ✓ The amount of water in the green roof soil is a significant influence .	• Needs to be maintained regularly. • Must be added to the initial structural calculation.

Even though Gulf residential buildings use almost twice as much power as their international counterparts, the majority of the NZEHs discussed in earlier research have successfully achieved zero-energy status via the implementation of active and passive measures. Most of the examples started the design phase by improving the quality of the building envelope. They subsequently implemented passive measures such as cross-ventilation and the stack effect using windcatchers and shading devices. Figure 3.25 provides a summary of the net zero options from prior research, which have been categorised into three primary divisions: passive approaches, building efficiency enhancements, and renewable energy sources. Each primary element has a secondary category in order to investigate the parameters in detail and depth.

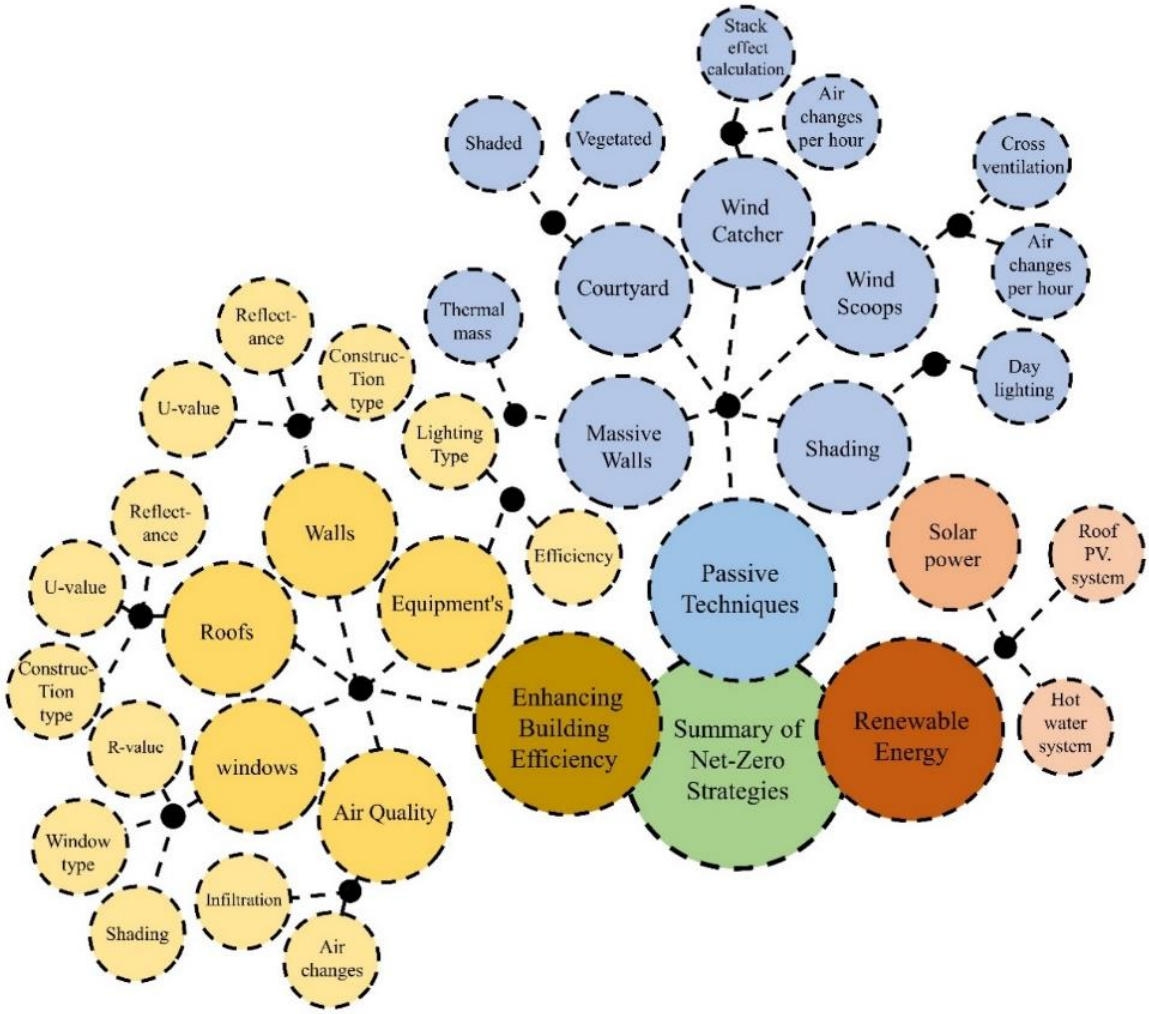


Figure 3.25 synthesis diagram summarises the previous work net zero strategies.

From a vast corpus of published material on NZEHs. This thesis has only evaluated articles that are relevant to this research during the design stage of a typical NZEH for the chosen case study. The purpose of evaluating those published studies is to help determine the methodology for the current research study. Considered articles devote a solid foundation for building Net Zero Energy Homes, containing essential information on the best framework, new technology, economic issues, and code compliance. Table 3.3 includes the previously evaluated precedent NZEH research comments and a perspective on each study to guide the approach and explain the framework.

Table 3. 3 Summaries of NZEHs Previous studies and the remarks that have been reflected to inform the research methodology.

NZEHs Previous studies		Study Remarks	Reflection to inform the research methodology
1	Casini-2020	Casini's ReStart4Smart home has the highest known energy efficiency method by more than 100%, with an Energy Use Intensity (EUI) of 43.9 kWh/m2 yr. The PV production system's net Energy Use Index (n-EUI) is 161 kWh/m2/yr. Under normal circumstances, the system can meet almost double the energy demands of the whole home.	Casini's study showed that the extra energy produced by home solar panels in the UAE could cover any increase in human consumption behaviour in real-life calculations, especially in the summer when the HVAC system consumption increases.
2	Alkhateeb-2019	Alkhateeb is converting an existing office building to achieve net-zero status. According to Alkhateeb's research, active measures are more effective than passive ones in lowering energy consumption. Passive parameters cut power usage by 14.7%, while active measures decreased demand by 63.2%.	Alkhateeb's prototype informs us that focusing on active measures is essential to reaching the net zero stage. Nevertheless, the passive measure should not be neglected when formulating the research methodology.
3	Belpoliti et al. -2019	In this study, they used another approach: the house is equipped with portable partitions to allow flexibility and maximization of space, resulting in the creation of a (buffer zone), which leads to a reduction of the cooled volume and, consequently, a possible energy-saving.	Flexible space sizing design and spacing adjustment result in decreased home energy consumption. The methodology can be informed here: By adjusting the HVAC cooling zone, the home can reduce its cooling load.
4	Feng-2019	This study examined 34 instances of Net Zero Energy Buildings (NZEB) from various locations worldwide. Most NZEB examples exhibited an annual energy consumption below 100 kWh per square meter of floor area at the site. Furthermore, several buildings achieved a net-positive energy status worldwide.	Feng's NZEHs review paper showed that most houses examined began their design by applying energy-efficient measures first to make the home reach a low energy consumption state, which was around 100 kWh/m2/year. Renewable energy was then used to get the NZE stage.
5	Kristiansen et al, 2019	Kristiansen et al. conclude that Off-grid buildings make it easier to respond to what ZEB implies to the public. They clarify that net-zero energy must be achieved through inaccurate operation and include all energy requirements, especially plug loads.	This study showed that examining human consumption behaviour in real-life operations is essential, especially in summary, when individuals keep their HVAC system operating most of the time.
6	Alfaris, Juaidi, et al-2017	focusing on smart home technologies; this case study shows that implementing an intelligent home system effectively enhances the house's ability to control energy usage. The intelligent net-zero energy home consumes 78 kWh/m2 per year. These advancements result in a 37% reduction in energy consumption as a net-zero energy-building.	The home automation concept could be applied to the NZEH. As this study showed, by applying this concept, the home can control energy usage efficiently with an energy reduction that can reach a third of the ordinary energy bills.
7	Alrashed 2015	Alrashed states that his Saudi virtual houses consume nearly twice as much electricity as their international counterparts due to their size, type of dwelling, and occupant behaviour. Airshed stated that the Saudi climate does not prevent the use of ZEHs in the area.	This study showed that we should consider that we have a particular consumption behaviour in the Gulf region. Also, the region's unique harsh climate increases cooling energy bills in the summer.
8	Taleb-2014	Taleb used passive cooling methods to improve thermal efficiency. The IES program was the primary simulation tool. Those passive cooling	As this research methodology will adopt vernacular passive cooling strategies, Taleb's study showed that passive

		solutions reduced the cooling load by 9%, and yearly energy usage decreased by 23.6%.	cooling techniques could decrease the building's total cooling load and energy consumption.
9	Deng et al-2011	A ZERB model in Shanghai shows that solar panels can generate electricity to meet the model's demands. Indoor comfort results showed that the Shanghai model's temperature comfort can be met even in hot, humid weather.	This study showed that the Gulf's hot and humid weather will not be an obstacle to applying the concept of NZEH. Nevertheless, the home might need a dehumidification device to provide thermal comfort.

3.5-Summary

Although this chapter's measures have been conducted individually, they all interact toward decreasing the cooling load. Feasible planning and integration during the building envelope's design process is the solution to produce energy-efficient buildings since arrangements made at different stages of the building envelope's design can influence overall building energy consumption and performance. Moreover, selecting the most effective energy strategies will require an integrated evaluation of all energy-efficient measures as a package. For instance, the interaction between shading, glazing, and interior lighting elements can together influence the cooling load reduction from solar heat gains while reducing artificial lighting use by dimming or switching in response to daylight intensity. When parameters like this are evaluated as a package, they have higher efficiency regarding energy conservation and materials cost feasibility. Across most of the reported case studies, the building achieves a low level of energy usage, averaging 70 kWh/m2/year. According to Krarti et al., the average Energy Use Intensity (EUI) for the Saudi climatic zone is around 150 kWh/m2/year. Therefore, these Net Zero Energy Homes (NZEHs) have reduced the EUI by 53%. Active methods have generally shown greater efficacy in lowering energy consumption than passive alternatives. In the Alkhateeb scenario, implementing passive parameters resulted in a 14.7% decrease in power consumption,

whilst active measures led to a significant reduction of 63.2% in electricity demand. Moreover, the use of Smart home technology in the area has significantly affected decreasing energy usage. The bright net-zero energy house, developed by Alfaris, Juaidi et al., has an energy consumption of 78 kWh/m2/year. This is in comparison to the baseline energy usage index of 107 kWh/m2/year as defined by ASHRAE 100-2015. These solutions enhance energy efficiency by 37% as compared to the ASHRAE norm for single-family villas. Conversely, several instances in the Middle East and East Asia have shown that indoor thermal comfort may be achieved even in hot and humid climates, as exemplified by the example of the Shanghai model. Furthermore, NZEHs may be effectively implemented in the hot and humid temperatures of the Gulf region. Alrashed determined that the Saudi environment does not pose a hindrance to implementing Zero Energy Homes (ZEHs) in the area. Nevertheless, the absence of specific energy efficiency standards and norms in the Gulf area poses a challenge in accurately assessing and evaluating energy use, since no benchmark is available for comparison within the same climatic conditions

CHAPTER 4

Research Methodology

4.1-Introduction

This investigation aims to explore the feasibility of implementing Net Zero Energy Homes (NZEHs) in the hot and humid environment of the Gulf region. This research establishes the foundation for a comprehensive guideline outlining an approach for constructing a residential home with net zero energy in this particular environment. The study offers reliable and measurable data on the techniques used to create Net Zero Energy residential buildings, specifically in this particular climatic region. This chapter explores the fundamental research principles and procedures often discussed in the literature on building environment research and their practical implementation. It employs a methodical strategy at different phases to accomplish its purpose and objectives effectively. Furthermore, it examines the several viewpoints that constitute the perspective of this investigation and then explores and distinguishes between the qualitative and quantitative research methodologies to be chosen. Lastly, a base case will be collected and designed following the selected approach using several parameters to make it a benchmark for designing the NZEH prototype. At the end of this stage, the base case will be validated and compared

with another researcher's model to have a more comprehensive overview of the accuracy of performance and modelling.

4.2-Research philosophy and methods

Numerous approaches provide satisfactory outcomes that are applicable across all study categories. However, to provide high-quality research outcomes, the selected approach must be compatible with covering all aspects of the NZEH concept. In addition, the approach must satisfy the study objective and include all of the data gathering and analysis. There are several perspectives within the research community about using appropriate perspectives for research philosophy. The fundamental categorisation of research methodologies in literature consists of qualitative and quantitative methods. When these two methods are combined, it is known as mixed methods (Neuman, 2006). As Creswell (2009) mentioned, the qualitative research technique explores and comprehends the significance that people or groups assign to a social or human situation. Qualitative techniques aim to explain the underlying causes of events, processes, and configurations, including ascertaining the interpretations and significance that individuals attribute to them. Qualitative research systematically collects, categorises, and analyses textual material from conversations or observations. In contrast, using a piece of equipment, the quantitative research technique evaluates objective ideas by analysing the connection between measurable variables. This allows the data to be evaluated using mathematical and statistical methods (Creswell, 2009). Quantitative research employs the scientific method, whereby a preliminary examination of the theory and literature produces specific goals, objectives, and testable hypotheses (Fellows & Liu, 2008). In this research investigation,

the data collection and analysis phases need the use of both methodologies, namely mixed methods. See Figure 4.1 for the implementation of the approach used in this study.

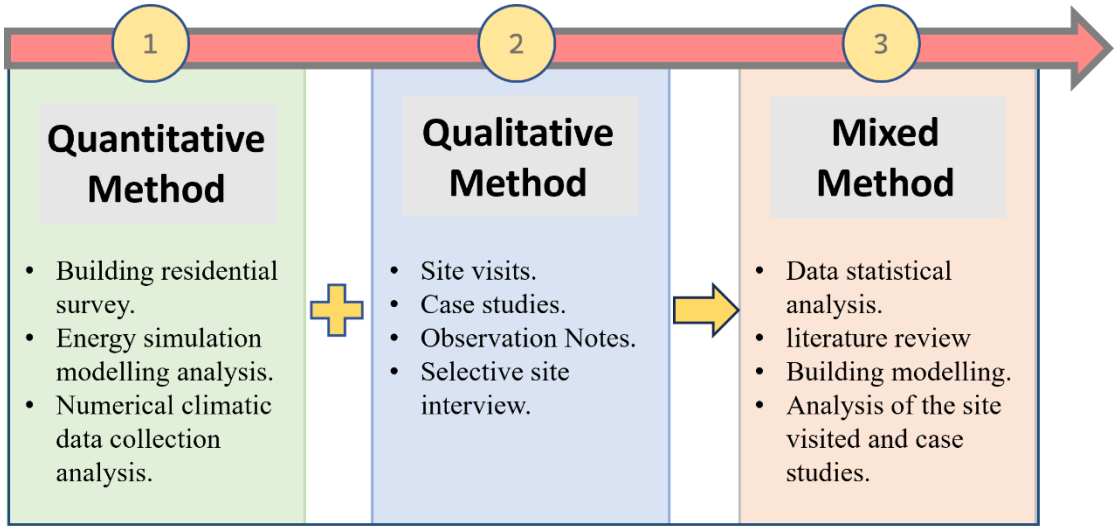


Figure 4. 1 Overview for Implementation of the approaches used in this study

This study employs a multi-method research strategy integrating quantitative and qualitative approaches. Mixed methods include research procedures that incorporate elements extracted from two different approaches. Integrating quantitative and qualitative investigation approaches enhances the capacity to communicate information tangibly. Moreover, employing a mixed methodology may improve comprehension of the phenomena under investigation, mainly when a comprehensive examination is unattainable by a single scientific technique. One might also claim that combining research methodologies offers the benefits of each approach and addresses their inherent shortcomings by using another method that aids in gaining insights, obtaining findings, and forming inferences or drawing conclusions (Fellows & Liu, 2008). Therefore, it becomes apparent that a mixed-method approach, which combines qualitative and quantitative methods, is required for this study. The mixed-method process involves using several

research practices, usually involving many stages that vary in their approaches and techniques, to create a more comprehensive data analysis synthesis of the research work.

4.3-Research Methodology Stages

The research methodology is divided into three stages to meet the main research aims and objectives. Each step requires a specific research tool to answer the related research question and fulfil the specified purposes.

Stage one, the initial stage of the research, begins with understanding the specific topics of the research area, including answering the research questions about how our ancestors managed to live in the Arabian Gulf's harsh climate region by utilising only passive cooling approaches. This part of the research will highlight the possible passive cooling techniques that can be applied to NZEH. Our ancestors' way of living will be analysed through site visits and case studies. Moreover, it is necessary to understand the concept of NZEH, including the system components, by investigating some regional projects to identify the best practices and make final remarks. Furthermore, in understanding the concepts of NZEH, it is essential to highlight some of the EEM and renewable energy techniques suitable for our climate conditions.

Stage two consists of investigating the actual construction practices in the region and establishing a base case to be a reference point for NZEH. This considers the cultural context in KSA and the Gulf region in general, with the unique norms that are traditional in culture and centred around religious solid practices and legislations as a focal element that shapes daily lifestyle, including the building design criteria and energy consumption behaviour. Therefore, it is vital to identify the parameters influencing building design

criteria and energy consumption in the domestic sector. To comprehend this research element, a public residential building survey and questionnaire will be distributed and analysed; this allows us to identify the physical and practical factors influencing energy consumption in the domestic sector and the tenant's views towards applying such sustainable projects in the region. Moreover, a site visit for recent regional residential building projects will be undertaken to address the actual construction practices. Consequently, a base case will be designed based on the gathered data and validated by comparing it with other research models to determine its EUI's tolerance compared to other regional examples. At the end of this stage, an energy simulation tool will be selected based on NZEH designing requirements and criteria.

Stage three, an NZEH simulation model suitable for hot and humid climates, will be designed and investigated using the computer modelling tool IESVE. The computer model incorporates the principles that have been gathered and comprehended in the previous stages, including passive cooling techniques, EEM, and renewable energy, to identify to which extent the NZEH can be achieved in the Arabian Gulf region. Moreover, the reduction in carbon emissions will be estimated and compared with the conventional home and other research models. Furthermore, to estimate the NZEH payback period, a detailed cost estimation for the whole building's system will be undertaken, which will be compatible with the updated price of the local market. At the end of this stage, a final recommendation and remarks will be gathered as a framework and a guideline to promote the implementation of NZEH in the Arabian Gulf region and hot and humid climates in general (see Figure 4.2), which shows the research methodology diagram divided into three stages to meet the main research aims and objectives.

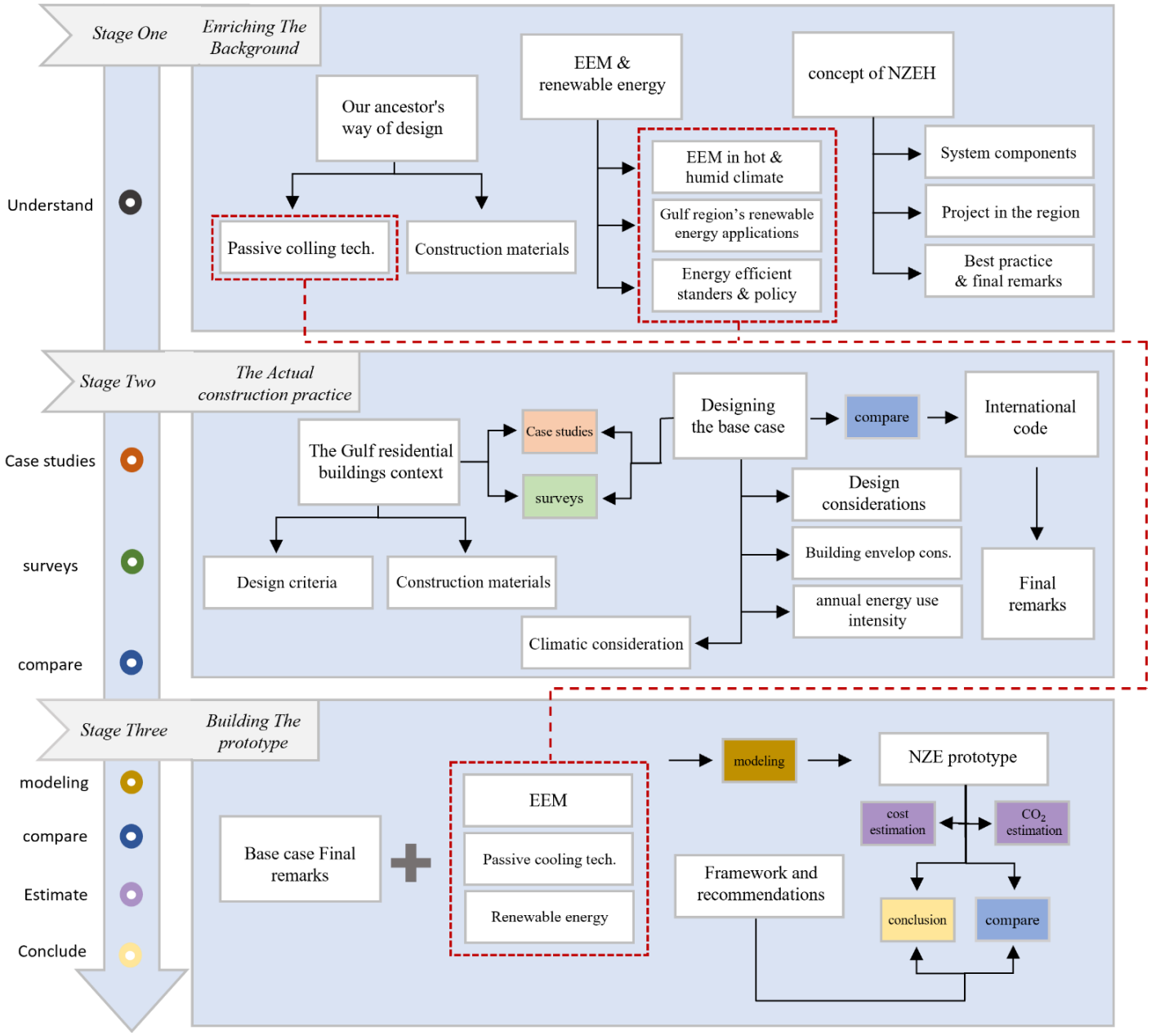


Figure 4. 2 The research methodology diagram - is divided into three stages to meet the main research aims and objectives. Each step will require a specific and different conducting tool to answer research questions and fulfil a specified purpose.

4.4- Residential Buildings Survey

This survey aimed to identify the main features of a typical home in Dammam, Saudi Arabia, and highlight the opportunities and challenges of implementing NZEHs from the residents' perspective. The survey includes several questions arranged into three sections: demographical parameters, dwellings' status, and the homeowners' viewpoints on applying ZEHs in Saudi Arabia. So many factors shaped and influenced the structure of questions in this survey, including the individual's demographic elements such as age, gender, marital status, education level, profession, monthly income, and family size. Moreover, regarding the dwelling's status, some critical aspects were included to cover the home resident's status, such as type of dwelling, size of dwelling (Area and Floor Number), tenure and finance of dwelling, type and number of Internal spaces, building systems (HVAC/lighting/appliances) and dwelling energy consumption rate including the monthly energy bills and the difference rate between summer and winter.

Moreover, some questions were shaped to reflect the individual consumption behaviour trend, including whether individuals turn appliances off when the home is unoccupied. These appliances include the HVAC system, water heater, lighting, and whether the tenants keep the water boiler working in the summer. Furthermore, some of the questions were asked to reflect the tenant's awareness of the energy rating card of their HVAC system and appliances.

On the other hand, to have a broader perspective regarding the individual views toward applying the NZEH concept. Some essential elements formulate the questions in this section, such as Concerns about environmental issues, including Support to mitigate environmental problems, Views toward the application of NZEHs, the use of energy efficiency measures, including passive cooling techniques and the application of renewable energy technology, including insulating solar panel and wind turbine (see figure 4.3).

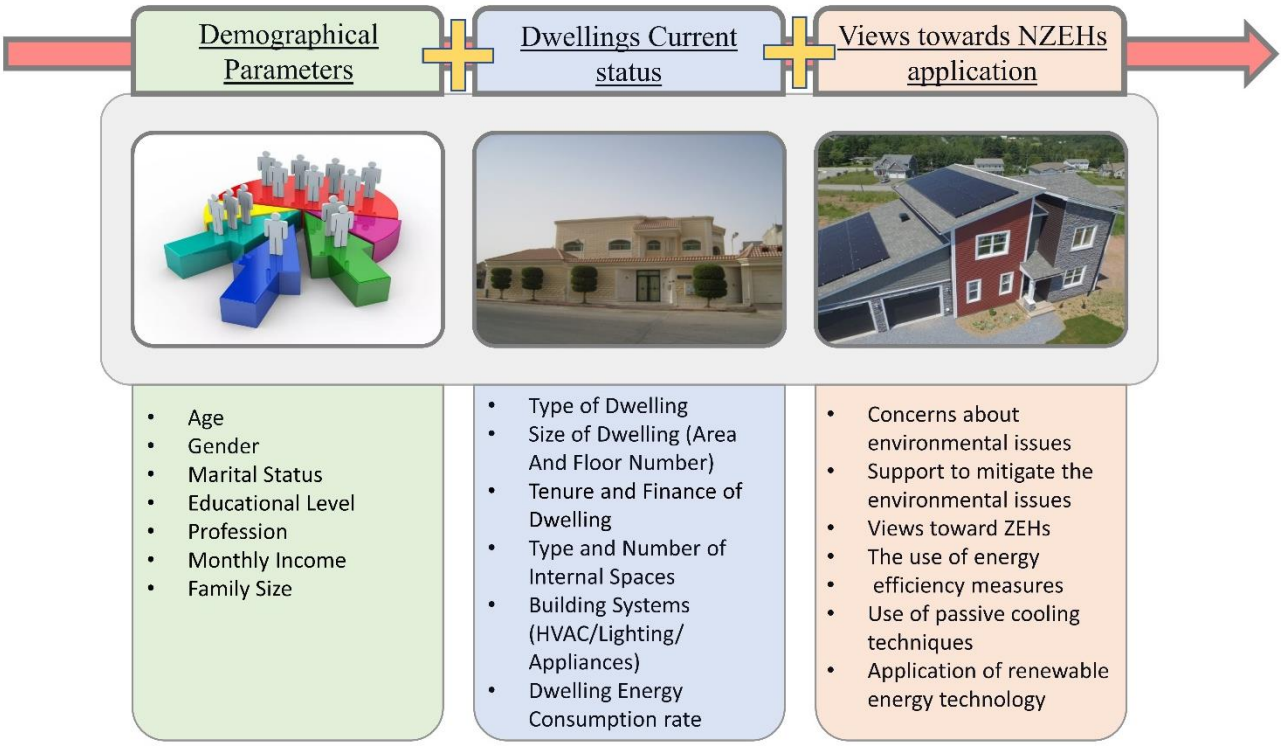


Figure 4. 3 Overview for the resident's survey key parameters.

The sample size is estimated using the Cochran equation, which enables calculating an ideal sample size given a desired level of precision, confidence level, and the expected proportion of the attribute present in the population (Cochran, 1977). This survey targets homeowners. According to the Saudi General Authority for Statistics, in 2017, the number of residential buildings in Dammam City was 167157.

Using the Cochran formula, the number of the households surveyed is determined as follows: $n_o = \frac{Z^2 P q}{e^2}$ (4.1)

Where:

- n_o sample size
- e is the wanted level of precision (the margin of error)
- p is the (expected) proportion of the population which has attribution in question,
- q is 1 – p.
- Z is Standard Normal z-table which is can determinant by knowing (e)

In this survey, it is assumed that half of the households will participate to obtain maximum variability. Hence, a probability p of 0.5 with 90% confidence, and the level of precision (error margin) of at least 7%. A 90 % confidence level equates to Z-values of 1.64 (from normal distribution table). Therefore, the sample size, n_o, It is computed to be: 138

Therefore, more than 200 questionnaires were distributed randomly amongst the residents in Dammam city (see Appendix A). The sample size required for this survey was calculated to be about 138 respondents. To accomplish broader segments of targeted participants, some of the questionnaire's terminology was designed in English and the local language, Arabic. The survey was conducted between November 2021 and February 2022, engaging online-based and face-to-face approaches. The number of participants who completed the questionnaire survey is 152. The survey was conducted and designed using the Google Form feature, and some parts were analysed using the SPSS statistical program.

4.5- Design of a Typical Base Case

This section focuses on developing a base case for a net-zero residential building. The key aspects and designing features for the conventional base case will be carried out from the residential case studies and the residential building survey that has been distributed and analyzed. Moreover, the Saudi building code that has been established since 2018 is going to be examined and included in designing the essential aspects. Also, other researchers' previous models will be compared to identify the main elements of the base case. Figure 4.4 illustrates the main elements involved in developing the base case as follows:

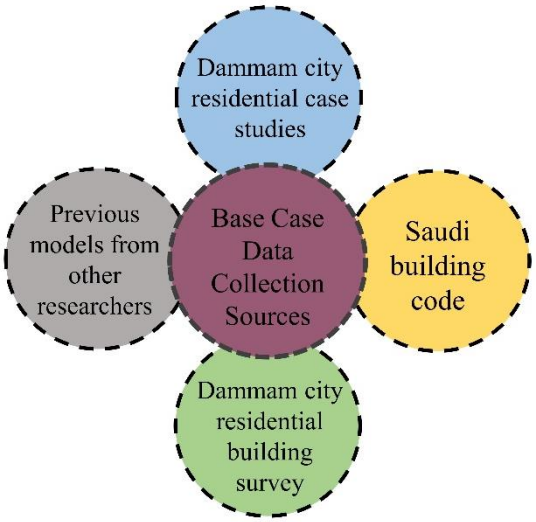


Figure 4. 4 The Base case Data collection is taken from four different sources.

This section will cover all the base case main design parameters, including the building geometry and functional spaces, Construction materials, Heating, ventilation, air-conditioning system (HVAC), and electrical system, including lighting. Each designing parameter contains secondary key aspects that will be examined in detail to ensure that all base case aspects are covered (see Figure 4.5). After designing the base case, the model will be compared with other research models to ensure its precision.



Figure 4. 5 Base case main designing parameters and key aspects.

4.5.1- Base Case Geometry and Functional Spaces

Residential buildings in Saudi Arabia and Dammam city are usually built with flat roofs since the region receives only 100 mm of rain yearly. As shown in figure 4.6, a pitched roof is uncommon and only used as an aesthetic figure usually built above the building entrance. In terms of building direction, usually, it depends on the client's preferences. Nevertheless, since the Saudi Arabia location, the Northeast elevation is the best because it receives less solar gain during summer. On the other hand, the south elevation is better if the elevation is shaded with overhangs. The southern elevation can perform efficiently during the whole year. In detail, During summer, the south overhangs will block the solar rays, decreasing the solar heat gain. Moreover, During the winter, when the sun-bath goes further down under the overhangs, the solar rays will penetrate through the building, which will help heat the building naturally.



Figure 4.6 Murjana Residential Complex showing the buildings geometry (Dammam city).

In gulf countries, functional spaces have a special and unique condition regarding privacy levels and synthesis. Internal spaces have different levels of privacy, which vary between public, semi-private, and private. Usually, the front half of the ground floor, including the

guest room, is for public visitors. Moreover, the back half of the ground floor, containing the living room and the kitchen, is considered semi-private since it's for family use only. On the other hand, around 80% of the second-floor area is usually considered private since it contains all the house bedrooms see Figure 4.7 which shows the base case's privacy levels with space synthesis.

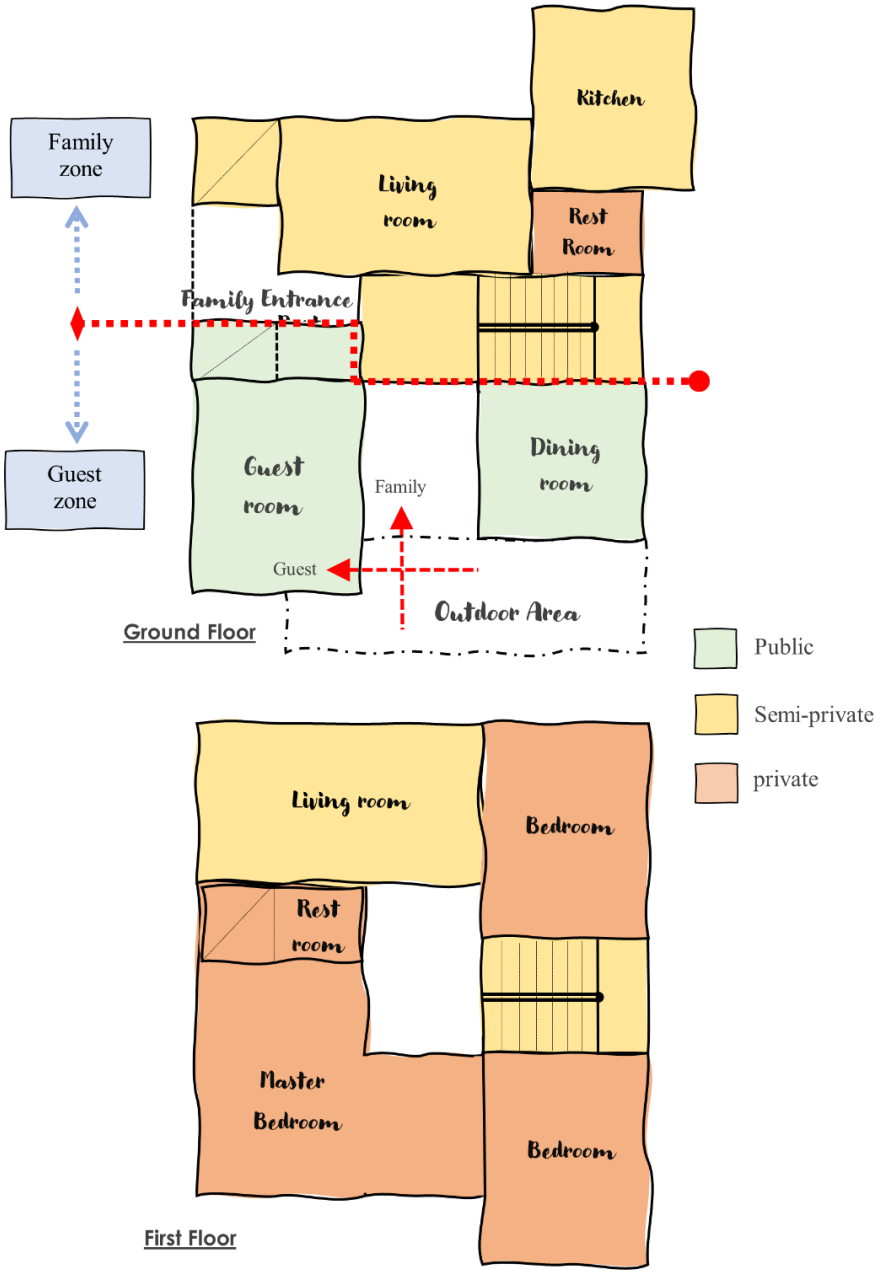


Figure 4. 7 Base case common zoning distribution and privacy levels with spaces synthesis (author's source).

In terms of interior spaces size and number, the data were taken both from the Dammam city residential survey and the "skakni" program case studies. After the data collection, results revealed that some functional spaces have a mean number less than 0.5, which indicates that those spaces are not widely in use, such as the external kitchen, office, and Annex room. Subsequently, spaces with a mean number less than 0.5 have been eliminated from the Base case. Moreover, the majority of "skakni" program case studies do not have a women's guest room since men's guest room can be utilized for women, and also the living room can be utilised as a women's guest room (see table 4.1). Subsequently, one guest room is going to be included in the design for both men and women.

Table 4. 1 Base case Mean interior spaces size and number according to Dammam city residential survey and "Sakani "residential program case studies.

Functional space	Spaces Size (Mean)	Spaces Number (Mean)
Bedroom	4.2 x 3.6 m²	3
Master Bedroom	6.6 x 3.8 m²	1
Living room	3.6 x 4 m²	1.5
Guest room	5.5 x 4.4 m²	1.2
Women guestroom	Excluded, according to case studies.	
Dining room	4.2 x 4.2 m²	0.9
Internal kitchen	3.8x 3.6 m²	1
External kitchen	Excluded, less than 0.5	
Multi-purpose room	Excluded, less than 0.5	
Bathrooms/toilets	1.60 x 2.2 m²	2.7
Laundry	2.8 x 1.80 m²	0.6
Office	Excluded, less than 0.5	
Storage	1.20 x 2.40 m²	0.9
Maid's room	2.8 x 3m²	0.6
Driver room	Excluded, less than 0.5	

The mean floor area for the residential building case studies examined previously is between 110 and 130 m². Moreover, most of them have a garage with a front yard between 30 and 50 m². On the other hand, a few case studies have a backyard. Nevertheless, some of the projects have a small backyard with an area between 15 and 25 m². Below is the final base case layout after engaging most of the geometry designing aspects (see Figure 4. 8-10)

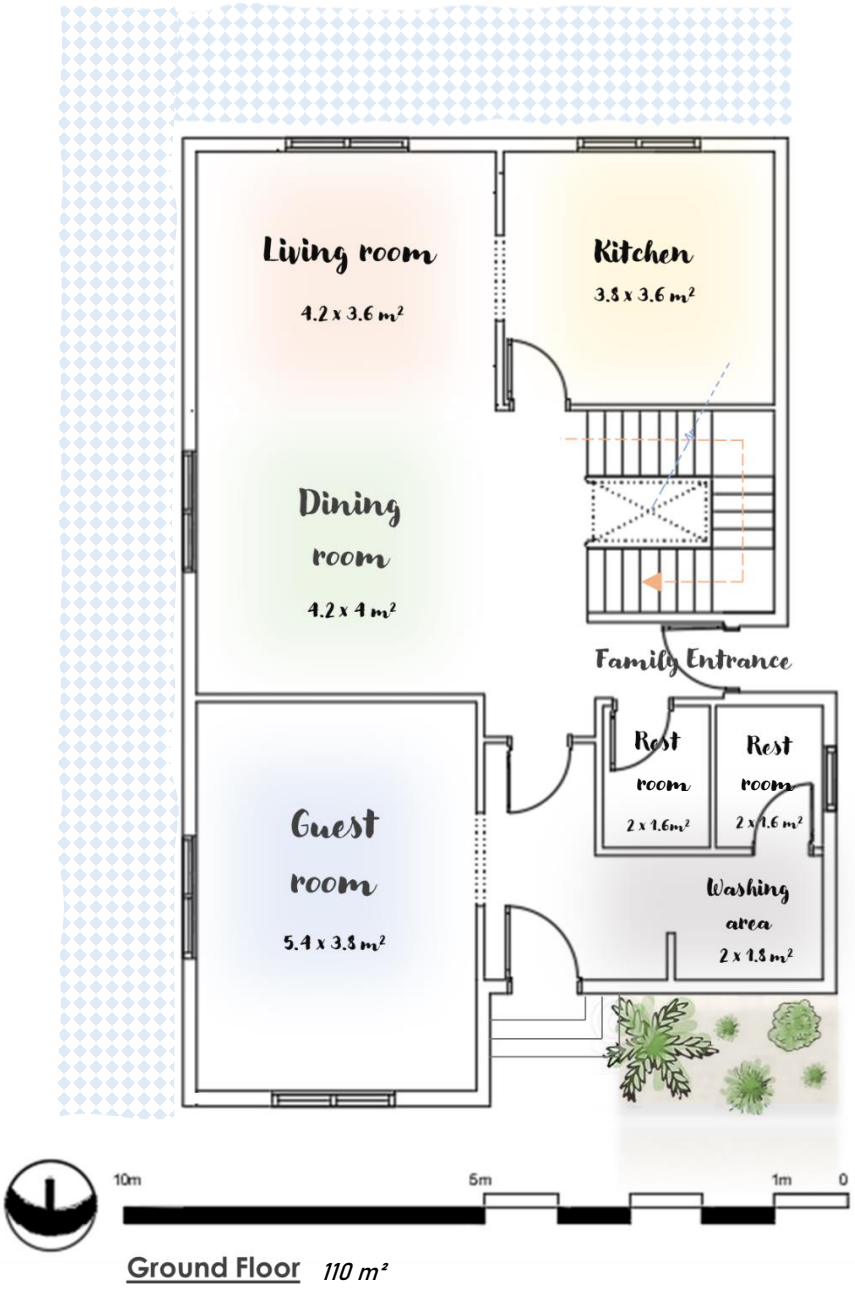


Figure 4. 8 2D layout of the proposed base case ground floor plan.



Figure 4. 9 2D layout of the proposed base case first floor plan.

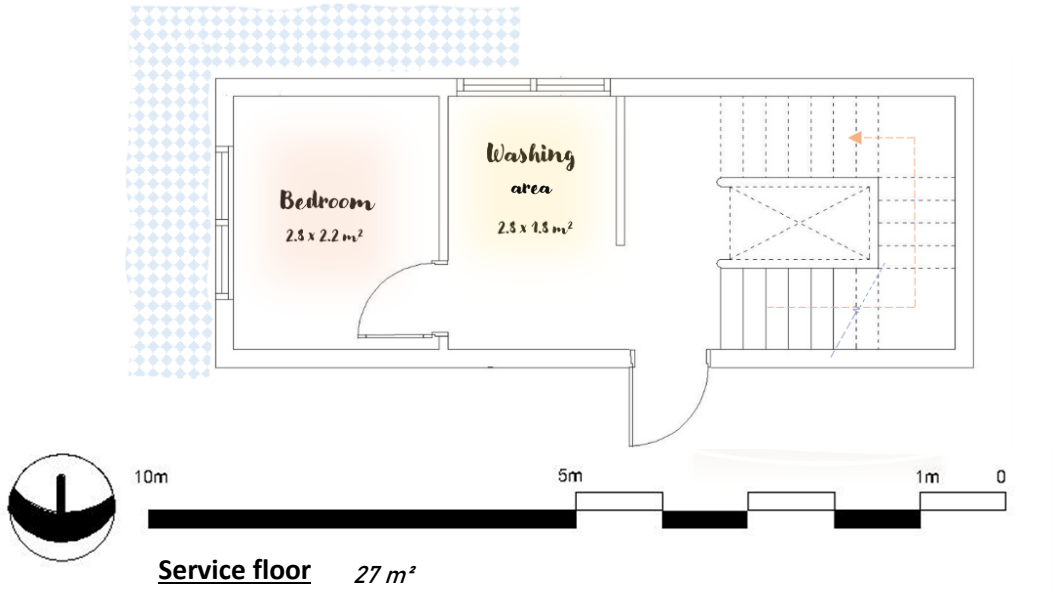


Figure 4. 10 2D layout of the proposed base case service floor plan.

4.5.2- Base Case structure and construction materials

According to the data gathered from the site investigation made to the ASWAR project and NSAAG townhouse in Dammam and Al Khobar City, both projects are constructed from reinforced concrete as a building skeleton structure and concrete blocks for the building envelope. The external walls consist of 40x20x20 cm sandwich concrete blocks, while the internal walls are 10cm concrete blocks (see figure 4.11).

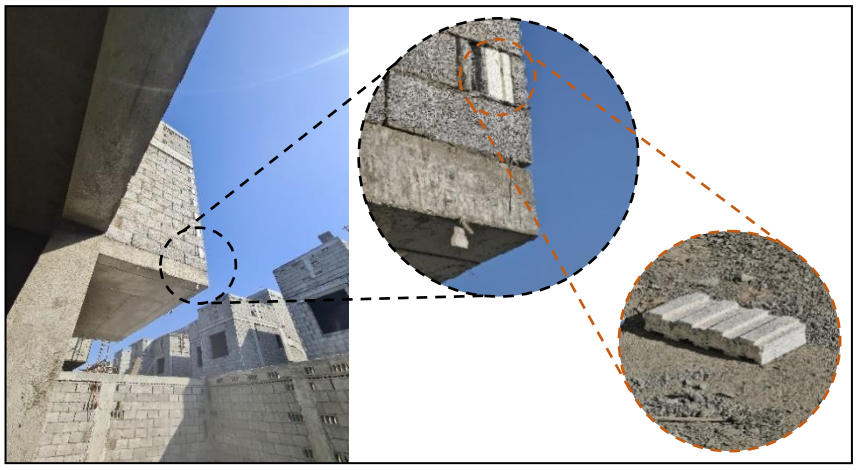


Figure 4. 11 NSAAG townhouse project building's envelope construction type (Al Khobar city) .

Moreover, Floors and roofs vary between the two projects (see Figure 4.12). In the NSAAG project, the roof is made of 30 cm flat slap reinforced concrete, while in the ASWAR projects (on the left), it is made of a 35cm Ribbed slap. Table 4. 2 shows the Thermal properties of common materials used in construction in Saudi Arabia.



Figure 4. 12 Both ASWAR & NSAAG projects building's roof structure type (Al Khobar city).

Table 4. 2 Thermal properties of common materials used in construction in Saudi Arabia (ASHRAE, 2009).

Material	Thickness (m)	Conductivity W/(m.K)	Density (kg/m3)	Specific heat J/(kg.K)
Terrazzo tiles	0.025	1.80	2560	790
Granite tiles	0.020	2.90	2650	900
Mortar	0.025	0.88	2800	896
Stucco	0.025	0.72	1856	840
Bitumen layer	0.004	0.43	1600	1000
Heavyweight concrete	0.150	1.95	2240	900
Concrete block	0.200	1.11	800	920
Gypsum board	0.015	0.16	640	1150
Expanded polystyrene (EPS)	0.050	0.03	40	1470

Table 4. 3 U-Values and descriptions for common building construction layers in Saudi residential buildings.

Construction element	Description	*U-Value (W /m ²K)
External wall	25mm stucco+200mm sandwich concrete block EPS filled core +25mm stucco	0.38
Internal wall	25mm stucco+lOOmm concrete block+25mm stucco	1.97
Roof	25mm terrazzo tiles+25mm mortar+ 4mm bitumen layer+ EPS 50 mm +150 mm cast concrete +25mm stucco	0.47
Internal floor	25mm carpet with no pad+25mm mortar+150mm cast concrete+200mm concrete block+25mm stucco	0.299
Ground floor Slab	25mm terrazzo tiles+25mm mortar+100mm cast concrete	1.25

* The U values provided in the table are according to the eQuest energy simulation program calculation method, which was calculated depending on the construction layers input, which is provided in the table above.

Table 4. 4 U-values & descriptions for typical doors and windows construction lyres in Saudi residential buildings.

Element	Description	* U-Value (W/m²K)
External door	Aluminum door with thermal break	1.8
Internal door	40 mm wooden door with wooden frame	1.3
External windows	Openable double glass windows (6mm/thermal gap/6mm)	0.47

Typically, the external doors in Saudi houses can be made of wood, aluminum, or steel. However, aluminum has become the most common choice for exterior doors in modern constructed homes because it provides lightweight and strength at the same time, while internal doors are mainly made of wood. Windows are usually double-glazed with an aluminum frame. Opaque doors in the building envelope shall have a maximum U-factor of 2 w/m2 · K. (SBC 601).

Regarding building construction code, the Saudi building construction code suggests that insulation must be in continuous layers for all building envelop except the thermal bridges like structural beams and columns. Nevertheless, most of the building insulation methods in Saudi Arabia are considered wrong practice since they are installed in uncontinuous forms, like using the sandwich concrete blocks as viewed previously in the NSAAG project. In terms of construction materials U&R values, the SBC updated the requirements of the values recently in 2021 yet, duo to the lake of insulation materials in the market that can meet the criteria, the SBC 601 for the low residential building U&R values has been suspended in 2022 untile they reviewed the market insufficient insulation materials. see table 4. 5-6) for SBC's Building envelop U-value and R-value requrments .

Table 4. 5 Building envelop U-values requirements according to the Saudi building code.

U-value coefficient (w/m²K)						Saudi Building code (updated-2021)
Zone 3		Zone 2		Zone 1 (Dammam city)		
Roof	Wall	Roof	Wall	Roof	Wall	
0.397	0.698	0.348	0.591	0.272	0.511	601 Non-Residential
	0.591		0.511		0.454	601 Residential

Table 4. 6 Building envelop R-value's requirements according to the Saudi building code.

R-value coefficient (m²K /w)						Saudi Building code (updated-2021)
Zone 3		Zone 2		Zone 1 (Dammam city)		
Roof	Wall	Roof	Wall	Roof	Wall	
2.38	1.34	2.80	1.67	3.54	1.81	601 Non-Residential
	1.67		1.81		2.06	601 Residential

4.5.3- Heating, ventilation, and air-conditioning system (HVAC)

According to the data gathered from the Dammam city residential buildings site visits, most of the projects are delivered to the users without installing the HVAC system to engage more flexibility to the residents to select the desired system they like. On the other hand, the results from the survey revealed that the majority of the participants, about 73.5 %, use a split unit system and around 40% of individuals use a window-type air conditioning (AC) system. The table below summarizes the HVAC Requirements from the Saudi building code and ASHRAE code (see table 4.7) .

Table 4. 7 Base case HVAC system specifications and code requirements.

parameter	Description
Type of cooling & heating system	With a percentage of 73.5 between participants, the mini-split unit was the most desirable system conducted from the Dammam city residential survey.
Energy-efficiency	Air-cooled air conditioners and heat pumps, Cooling mode < 19,000 kW cooling capacity must have a minimum SEER of 9.7 & COP 2.80 (SBC 601)
Flow-rate	The minimum flow rate for a mini-split system is 8 1/s per person (Manufacturer).
Cooling and heating set-points	The cooling and heating set-points are respectively 24 °C and 20 °C (ASHRAE, 2009). Moreover, the cooling setpoints mean from the Dammam city residential survey was 23 °C
Air relative humidity	The minimum and maximum percentage saturation is respectively 30% <RH< 60% (ASHRAE, 2009).
Natural ventilation	Natural ventilation for all spaces is 0.15 1/s per m² (ASHRAE, 2009).
Infiltration rate	ACH Must be above 0.35 according to Saudi building code 601
Auxiliary ventilation	The auxiliary ventilation for kitchens is 50 1/s, and for toilets/bathrooms are 25 1/s (ASHRAE, 2009).
Energy of auxiliary ventilation	The energy for auxiliary ventilation is 1 W/(l/s) for kitchens, and 0.5 W/(l/s) for toilets/bathrooms (Manufacturer).

4.5.3.1-Demotic Hot Water (DHW)

Regarding the demotic hot water system, As the survey indicates, separate indoor units are the most desirable system in a domestic building with around 75%. On the other hand, an instant water heating system wasn't popular in democratic buildings. On the other hand, the daily DHW consumption for the Base case was calculated according to the Saudi building code 601 for Domestic hot water. The following input values, specific to domestic hot water, shall be used to calculate daily hot water consumption by gallons.

Temperature set point 24°C, 49°C.

Daily hot water consumption by Gallons = $(30\ a) + (10b)$ (4.2)

Where:

a = Number of domestic units in standard and proposed designs.

b = Number of bedrooms in each domestic unit.

Given that the base case has four bedrooms, the daily DHW consumption was calculated to be 70 gallons (about 265 litres per day).

4.5.3.2-Occupants' Heat Gain and Equipment Power Density

The average heat gain within the occupied space includes heat dissipated by occupants, which should be accounted for when assessing the building's cooling load. Average sensible and latent heat dissipates by occupants depending on the activity state and level. Data used in the present simulation is taken from ASHRAE standards, as shown in Table 4.8.

Table 4. 8 People sensible and latent heat gains depend on the type of occupant zone (ASHRAE, 2009).

Zone	Sensible heat (Watt/person)	Latent heat (Watt/person)
Living and guest zones	65	30
Kitchen zone	80	80
Sleeping zone	40	30

Likewise, heat dissipated from using various power equipment around the house contributes to the building's cooling load. This is specified as a power density in watts per occupied floor area as presented in (Table 4.9).

Table 4. 9 The power densities for main zones in the typical home (Monawar, 2001).

Zone	Power Density (Watt/m^2)
Living	7
Guest	5
Kitchen Zone	30
Sleeping Zone	7

4.5.3.3-Occupancy operation schedule and equipment usage patterns.

Users' behavior toward energy conservation plays a significant role in determining the total energy consumption. In fact, in a hot and humid climate, like the situation here in the Gulf region, the cooling profile is a crucial factor in determining the total energy consumption. Sadly, from the Dammam city residential survey, around 43% of users do not turn off their AC system even when the room is unoccupied or turn it off for less than two hours. As one of the research data collection limitations, most of the studies regarding operation schedules are outdated. Therefore, this investigation will depend on the survey user behaviour consumption to determine the operation schedule and from the (Monawar, 2001) study as a guideline.

4.5.4- Electric & Artificial Lighting

Regarding EUI, the value is most elevated in the East region, with 182.4 kWh/m2 /year and most subordinate in the Southern part, with 125.6 kWh/m2 /year (see Figure 4.10). The average EUI value for the housing stock in KSA is 149.6 kWh/m2 /year (M. Krarti et al., 2020).

Table 4. 10 (EUI) values for residential buildings by KSA region (M. Krarti et al, 2020).

Region	Floor Area (m2) x10^6	Annual Energy Consumption (TWh/year)	EUI (kWh/m2 /year)
Middle	354	48.187	136
East	151	27.619	182.4
West	312	49.935	160
South	137	17.313	125.6
KSA	956	143.054	150

Regarding artificial lighting, Dammam city residential survey showed that LED tends to be the most common option among participants, with a percentage of around 70%. This high percentage is due to the individual's awareness regarding artificial lighting energy consumption. LED has so many advantages compared to other artificial lighting types. They consume less power, require low operational voltage, and exhibit a long lifespan. In the table below, the Base case artificial lighting design has been calculated according to the VONN artificial lighting calculator (see Table 4.11).

Table 4. 11 Base case artificial lighting fixture type and power rating.

Occupied space	Length (m)	Width (m)	Height (m)	Type of lighting	No. of fittings	Power rating (w)	Lumens
Guest entrance	3.8	2.2	3.2	LED light	3	5	1460
Guest Majles	5.4	3.8	3.2	LED light	6	5	3694
Guest toilet	2.2	1.6	3.2	LED light	2	2.5	615
Living room (1)	4.2	3.6	3.2	LED light	4	5	2722
Kitchen	3.8	3.6	3.2	LED light	5	5	3284
Dining room	4.2	4	3.2	LED light	6	5	4000
Bedroom M.	6.6	3.8	3.2	LED light	7	5	4515
Bedroom (1)	4.2	3.6	3.2	LED light	5	5	2873
Bedroom (2)	3.8	3.6	3.2	LED light	4	5	2600
Bedroom (3)	4	4.8	3.2	LED light	4	5	2300
Living room (2)	3.6	2.8	3.2	LED light	2	5	1210
Washing area	2.8	1.8	3.2	LED light	1	5	605
Maids room	2.8	2.2	3.2	LED light	1	5	740

4.6- Base Case Computer Modelling and Validation

In this step, the energy-simulating tools will be selected based on some mandatory criteria and requirements in designing the NZEH. Moreover, the Base case simulation model will be validated by comparing it with a home in Dammam city and other research models. This process will have four main steps.

The First step examined the most widespread energy-simulating programs to meet the NZEH models' critical design parameters. Moreover, energy simulation tools will be selected to evaluate the base case energy consumption in this step.

The second step is to validate the energy simulation tool. Existing homes in Dammam City were compared regarding their actual energy consumption (actual electric bills from the provider) and the predicted annual energy consumption for the same house using the energy simulation tools.

In the third step, the Base case that has been built in the previous chapter is validated by comparing it with the predicted EUI for an existing home in Dammam city. Moreover, the validated Base case will be enhanced and developed to reach the NZE stage in the next chapter.

The fourth step evaluates the base case performance based on other researcher models regarding specification, parameters, and energy use intensity (EUI). This step assesses where the Base case stands in terms of energy consumption compared to other researcher models (see Figure 4.14) shows the Validating process in four main steps.

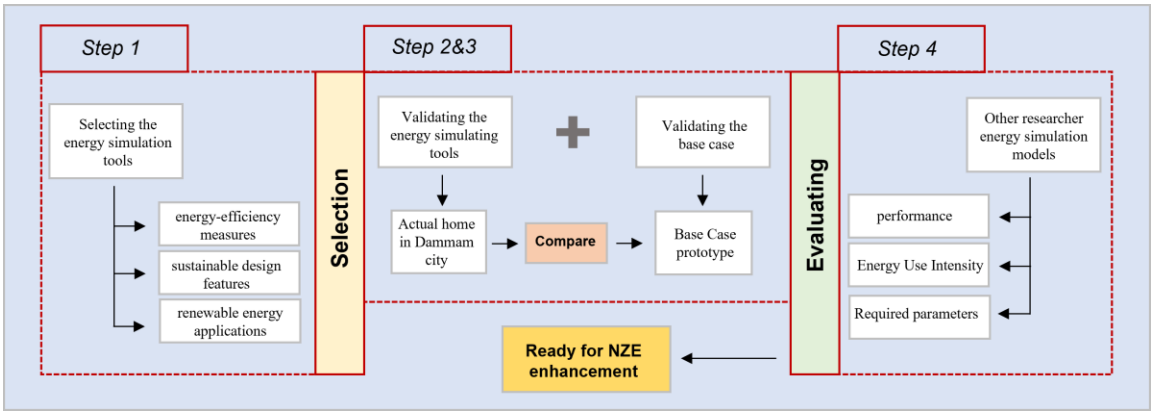


Figure 4. 14 Selecting the Energy Simulating Tool and Validating the Base Case simulation prototype process in four main steps.

4.6.1-Selecting the Energy Simulating Tool

Adopting an Energy simulation tool is essential in the building Analysis stage. Moreover, a careful selection process is required to choose the suitable tool for the proper requirements. Therefore, the energy simulation program's capabilities should be examined before the selection stage to meet the scheme specifications. This investigation aims to evaluate the performance of a ZEH in Dammam City, Saudi Arabia. The selection of an Energy simulation tool to Evaluate a ZEH performance depends upon some requirements and features to assess the design and implementation of such a building. The principle of a ZEH is achieved by reducing energy consumption, applying some sustainable design parameters and energy-efficient measures, and providing the required energy from on-site or off-site renewable energy recourses. Therefore, the selected tool should be able to simulate energy-efficiency measures, sustainable design features, and renewable energy applications. Furthermore, the simulation tool should have the feature of evaluating the environmental and economic situation of the buildings. As shown in Table 4.12, the most

popular energy-simulating programs were selected and examined to model the mandatory requirements. The comparison information was obtained from (Hijazi, 2018). Since energy simulation programs are growing, most examined programs meet the desired NZEH requirements, such as (energy-plus, ESP-r, IES, and TRNSYS) (see Table 4.12). For this investigation, the primary selected energy simulation (IES-VE) provides a more detailed output, easy access, and a less complex interface besides meeting the ZEH requirements. The IES (Integrated Environmental Solutions) simulation software application offers design experts a range of factors for analysing buildings. The model operates based on the geometric depiction of the building. The software tool enables users to engage with other modelling software tools. The simulation application includes Apache Sim, a program specifically designed for the dynamic thermal modelling of heat transport processes in buildings. Those tools help save time and enable a unified design approach for HVAC and ventilation systems, lighting and daylighting, CFD, and renewables. Another factor contributing to the choice of IES-VE is its extensive use at British institutions due to its origin in the UK. Moreover, it typically offers convenient accessibility to students in the United Kingdom via its collaborations with regional universities. However, in this experiment, the IES will be verified in a basic run of the DOE 2 American simulation program equest. Subsequently, all NZEH simulations in this study project will be conducted utilising the (IES-VE) energy modelling program.

Table 4. 12 The most popular energy-simulating programs were analyzed to meet NZEH mandatory requirements (Hijazi, 2018).

Features	Energy Plus	ESP-r	IDA ICE	IES	TRNSYS
Simulation solution					
Simulation of loads, systems and solutions	✓	✓	✓	✓	✓
Iterative solution of nonlinear systems	✓	✓	✓	✓	✓
Duration of calculation					
Variable time intervals for HVAC interaction	✓	✓			✓
Selection of building systems and user	✓	✓	✓	✓	✓
Dynamic variables based on transient solutions	✓	✓	✓		
Complete geometric description					
Walls, roofs and floors	✓	✓	✓	✓	✓
Windows, skylights, doors and external coatings	✓	✓	✓	✓	✓
Polygons with many faces	✓				
Imports of building from CAD programs	✓	✓	✓		✓
Export geometry of buildings for CAD software	✓	✓	✓		
Import/export of simulation models	✓	✓			
Calculation of thermal balance	✓	✓			✓
Absorption/release of building moisture	✓		✓	✓	
Internal thermal mass	✓	✓	✓	✓	✓
Human thermal comfort	✓	✓	✓	✓	✓
Solar Analysis	✓	✓		✓	✓
Analysis of Isolation	✓	✓	✓		
Advanced fenestration		✓	✓	✓	
Calculations of the building in general	✓	✓	✓	✓	✓
Surface temperatures of zones	✓	✓	✓	✓	✓
Airflow through the windows	✓	✓	✓	✓	✓
Driving surfaces	✓			✓	✓
Heat transfer from the soil	✓	✓			✓
Thermo-physical variable	✓			✓	
Daylighting and lighting controls	✓	✓		✓	✓
Calculation of coefficients of wind pressure	✓	✓	✓	✓	✓
Natural Ventilation	✓	✓	✓	✓	✓
Natural and mechanical ventilation	✓		✓		✓
Control open of windows for natural ventilation	✓	✓	✓		✓
Infiltration in multiple zones	✓	✓	✓		
Renewable Energy systems					
Solar Energy	✓	✓		✓	✓
Ground pipe ventilation system	✓				
Photovoltaic panels	✓	✓	✓	✓	✓
Hydrogen Systems		✓			
Wind Energy		✓			✓
Electrical Systems and Equipment					
Energy Production through R.E.	✓				✓
Management of electric power loads	✓	✓			✓
Electricity generators	✓	✓			✓
Network connection		✓			✓
HVAC Systems					
HVAC idealized	✓	✓	✓	✓	✓
A possible configuration of HVAC systems	✓	✓	✓	✓	✓
Repetitions cycle air	✓	✓	✓	✓	✓
Distribution systems	✓	✓	✓	✓	✓
Modelling and monitoring CO_2	✓		✓	✓	✓
Each distribution of air per area	✓	✓	✓	✓	✓
Forced air unit per zone	✓	✓	✓	✓	✓
Equipment Unit	✓	✓		✓	✓

4.6.1.1-Validation of the Energy Simulating Tools.

To validate the primary simulation tools selected in this research, a comparison was made between existing dwellings in Dammam City regarding the actual and predicted annual energy consumption for the same home using lES and equest energy simulation tools. The home architecture geometry and envelope properties were entered in both simulation programs. Moreover, both simulation programs used the same Dammam city weather file to operate the simulation. After the simulations, both programs predicted annual energy consumption compared to the existing dwelling's monthly bills. At the end of the comparison, both simulation programs showed promising results that were close to the dwelling's annual energy consumption. The selected dwelling is in Dammam City, Ash Shulah District, with a floor area of 136 m². The dwelling has two stories, usually occupied by four family members. The dwelling's annual energy consumption between 2020-2021 was 33140.7 kw/h/year, averaging 2760 kw/h/month (see Figure 4.15). The dwelling has a EUI of (146 kWh/ m²) which is considered reasonable compared to the Estimation of EUI for residential buildings based on data reported in Saudi Arabia from the 2010 Census, which was (195 kWh/ m²) (Krarti et al., 2019).



Figure 4.15 Dwelling location in the Ash Shulah Dist. Dammam city.

. For the home building envelope specifications, see Table 4.13, which shows the Actual dwelling's building envelope properties and construction elements description.

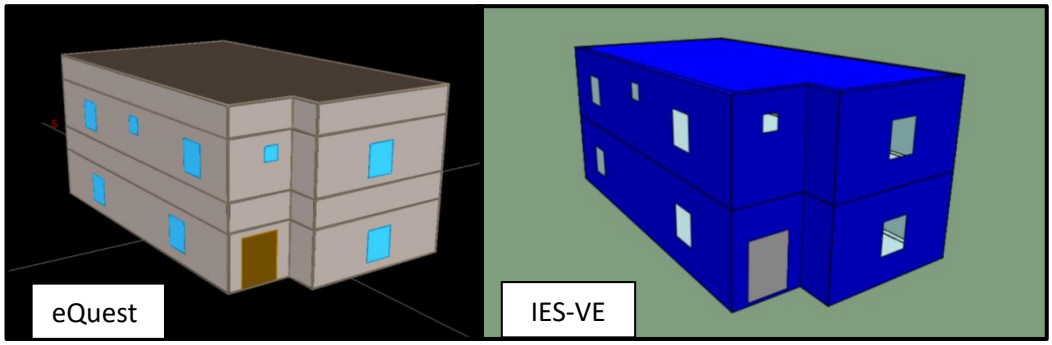


Figure 4. 16 The actual dwelling geometry from the IES & eQuest simulation tools.

Table 4. 13 Actual dwelling's building envelop properties and construction elements description.

Construction	Element Description	U-Value (W /m²*K)
External wall	25mm stucco+100mm concrete block+25mm EPS+100mm concrete block+25mm stucco	0.7
Internal wall	25mm stucco+l00mm concrete block+25mm stucco	1.97
Roof	25mm terrazzo tiles+25mm mortar+ 4mm bitumen layer+150mm castconcret +25mm stucco+25mm gypsum board	0.7
Internal floor	20mm marbel+25mm mortar+150mm cast concrete+25mm stucco	1.8
Slab on-grade	20mm granite+25mm mortar+100mm cast concrete	1.1

One data collection and research limitation was that obtaining the homeowner's detailed building envelope specification and U-values was challenging. So, the general construction material was entered into the simulation program, and the detailed U-values were predicted from the energy simulation program. The U values in the table are according to the eQuest energy simulation program calculation method, which was calculated based on the

construction layers input provided in the table above. For more details on the program input, (see Appendix B, C & D).

The existing dwelling's energy consumption bills were exported from the resident SEC app, which allows the resident to monitor their energy consumption and set a limit for their monthly energy consumption cap (see Figure 4.17). and new electricity tariffs for all building types as approved, as shown in Table 4.14.

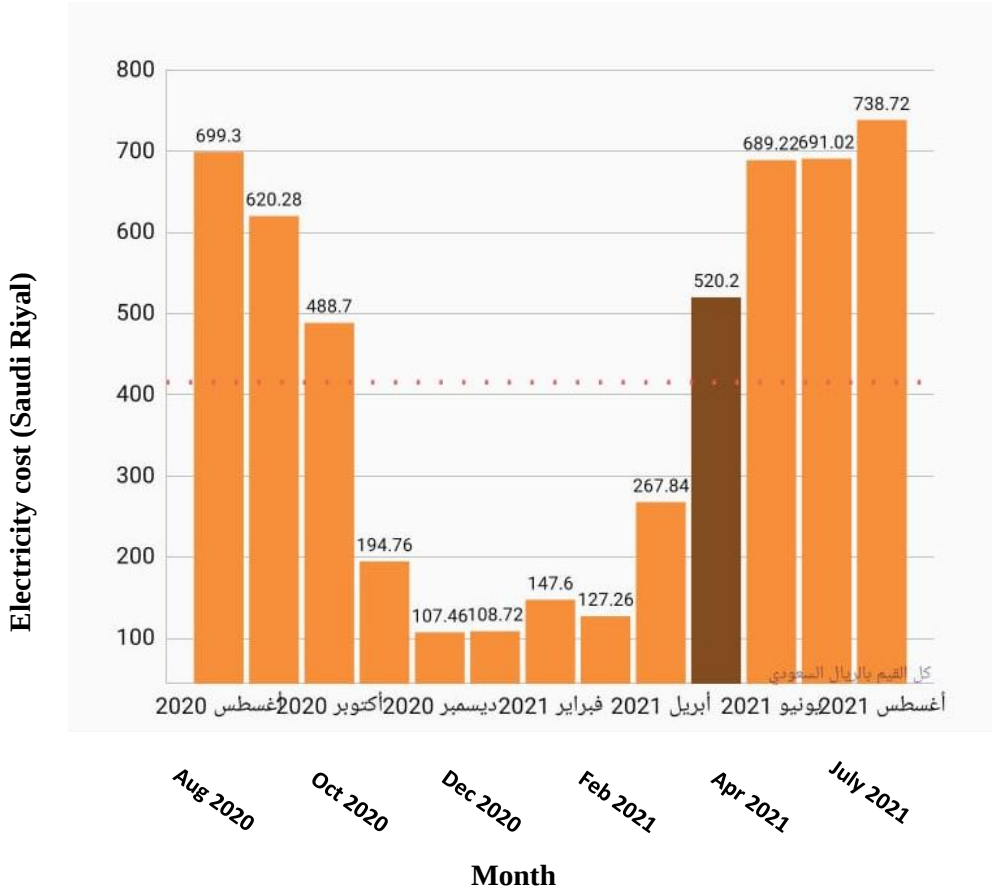


Figure 4. 17 The existing dwelling 12 months energy consumption bills by Saudi Riyals (SEC, 2021).

Table 4. 14 New Electricity Tariffs for all building types as approved by the Council of Ministers' Decree dated 12/12/2017, which has been applied since 1/1/2018 (SEC, 2018).

Consumption categories (Kwh)	Residential (Halalah / kwh)	Commercial (Halalah / kwh)	Agricultural & Charities (Halalah / kwh)	Governmental (Halalah / kwh)	Industrial (Halalah / kwh)	Private educational facilities, private medical facilities (Halalah / kwh)
Less than 6000	18	20	16	32	18	18
More than 6000	30	30	20			

The Dwelling 12 monthly energy consumption bills are converted from cost (SR) to consumption (kw/h) (see Appendix E). Using the tariff rate provided in Table 4.14 and the dwelling's annual energy consumption, the residence is in the (less than 6000 kWh/ month category), which sets the price for (18 Halalah/kw/h). See Table 4.15. This step calculates the total annual energy consumption for the home since the energy bills show only the monthly consumption by (SR). After that, the actual home's annual energy consumption will be compared with the energy simulation model's predicted consumption.

Table 4.15 dwelling 12 months energy consumption bills converted from cost (SR) to consumption (kw/h) using the tariffs rate provided in table 4.18.

Months	Cost. RS	Cost. Halal	Consum. KW/h
Jan	137	13653	759
Feb	181	18124	1007
mar	303	30300	1683
Apr	320	31952	1775
May	610	60973	3387
Jun	804	80410	4467
Jul	831	83137	4619
Aug	816	81570	4532
Sep	725	72482	4027
Oct	530	53000	2944
Nov	574	57351	3186
Dec	136	13580	754

Total	
33140.7	kw/h/year

The actual home input was entered in both IES and eQuest energy simulation programs. After the simulations, the results showed that The IES simulation tool prediction was 1% less than the home's actual annual energy consumption (see Appendix B&C). On the other hand, the eQuest energy simulation tool prediction was 4% higher than the home's actual consumption (see Figure 4.18).

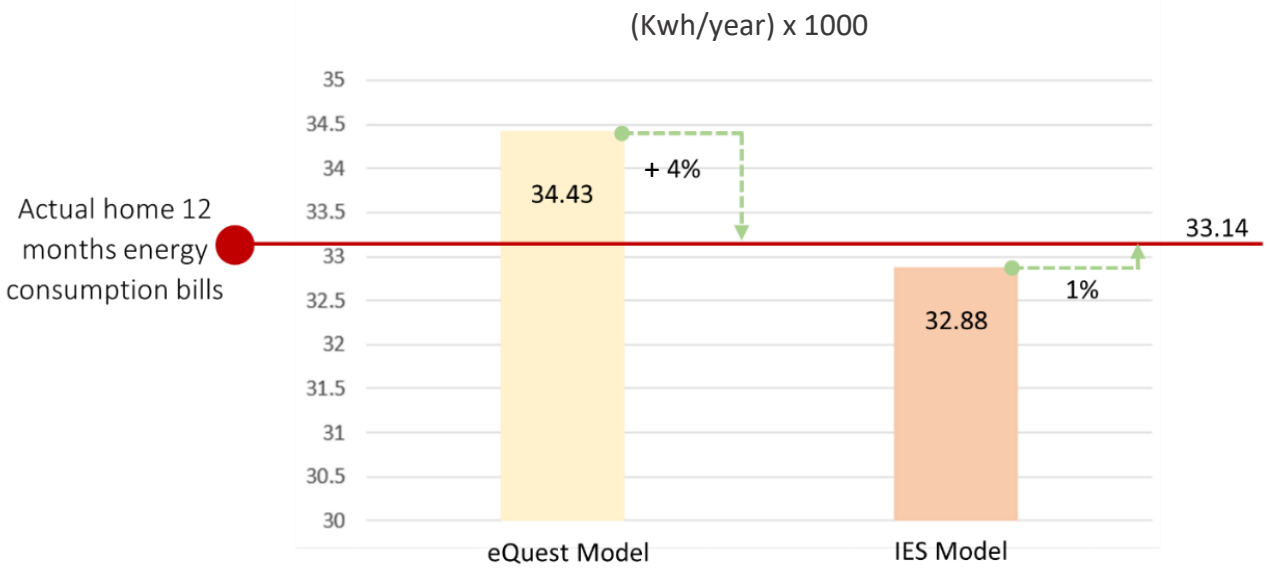


Figure 4. 18 The predicted annual energy consumption from both programs has been compared with the existing dwelling 12 months energy consumption bills.

4.6.2-Validation of the Base Case.

The base case specifications and criteria were developed in the previous section. In this step, an energy simulation model for the base case will be performed and compared with an actual Dammam City model made in the last step. The actual home and the base case have some differences in geometry and specifications (see Figure 4.19 and Table 4.16). The existing home chosen to simulate in the previous step does not follow the Saudi code established in 2018 since the home was built before that period. On the other hand, the base case was compatible with the Saudi code, which explains why the base case envelope has a better U-value than the actual home. Moreover, according to the site visit to the residential projects in Dammam city, most projects have a maid room on the roof with clothes washing room. Subsequently, the base case has more space on the roof than the actual home. For more details on the Base case energy simulation program's input, (see Appendix D).

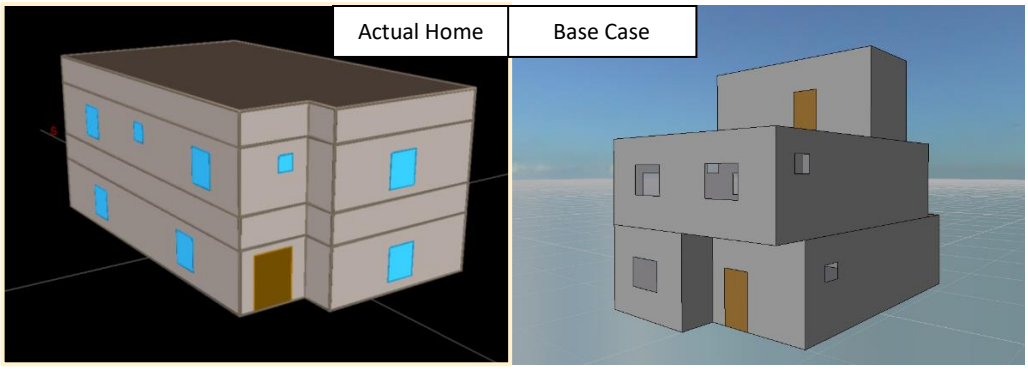


Figure 4. 19 Actual Building in Dammam city Vs the Base case geometry in eQuest and IES simulation tool.

Table 4. 16 compares specifications between the actual home in Dammam city and the base case.

Parameter	Dammam city actual home data	The Base case model
Location	Dammam city	Dammam city
Energy Simulation program	eQuest (DOE-2 based products)	IES
External wall U-Value (W /m ²K)	25mm stucco+100mm concrete block+25mm EPS+100mm concrete block+25mm stucco (0.7 W /m ²K)	25mm stucco+250mm sandwich concrete block EPS filled core +25mm stucco (0.41W /m ²K)
Double-glazed window system U-Value (W/m²K)	The selected designs are evaluated under high-performance double glazing (U-value= 1.317 W /m ²K , SHGC= 0.278)	Openable double-glass windows (6mm/ gap/6mm) (1.25 W /m ²K)
Window-to-wall ratio (WWR)	7% of the gross wall area	8 % of the gross wall area (31 m²),
Roof U-Value (W /m ²K)	25mm terrazzo tiles+25mm mortar+ 4mm bitumen layer+150mm castconcret +25mm stucco+25mm gypsum board (0.7 W /m ²K)	25mm terrazzo tiles+25mm mortar+ 4mm bitumen layer+ EPS 50 mm +150 mm cast concrete +25mm stucco (0.43 W /m ²K).
HVAC system	Residential System (Constant-Volume DX AC) with Electric Heating COP 3.5	Mini-Split Unit SEER of 3.6 & COP 3.49
Infiltration rate (ACH)	0.35 ACH (assumed)	0.25 ACH
Simulation set-point (heating and cooling)	24°C for Cooling, 21°C for Heating	23°C for Cooling, 19°C for Heating
Equipment power density	5 W/ m² guest zone, 7 W/ m² living & sleeping zones, and 30 W/ m² kitchen zone (Depending on space)	Lighting: 1.6 W/ m², Refrigerating: 1.8W/ m², cooking: 12W/ m², misc.: 4W/ m² People: 90W/ person.
Lighting power density		
Energy use intensity (kWh/m²/year)	146 (kWh/m² /year)	130 (kWh/m² /year)

After simulating the base case and the actual home, it appears that the actual home has an EUI 12% higher than the base case (Figure 4.20). This increase in EUI is due to the difference in building envelope specification between the two homes. The actual home has a u-value of 0.7 for the roof and walls. On the other hand, the base case has a u-value of 0.43 for the roof and 0.41 for the walls.

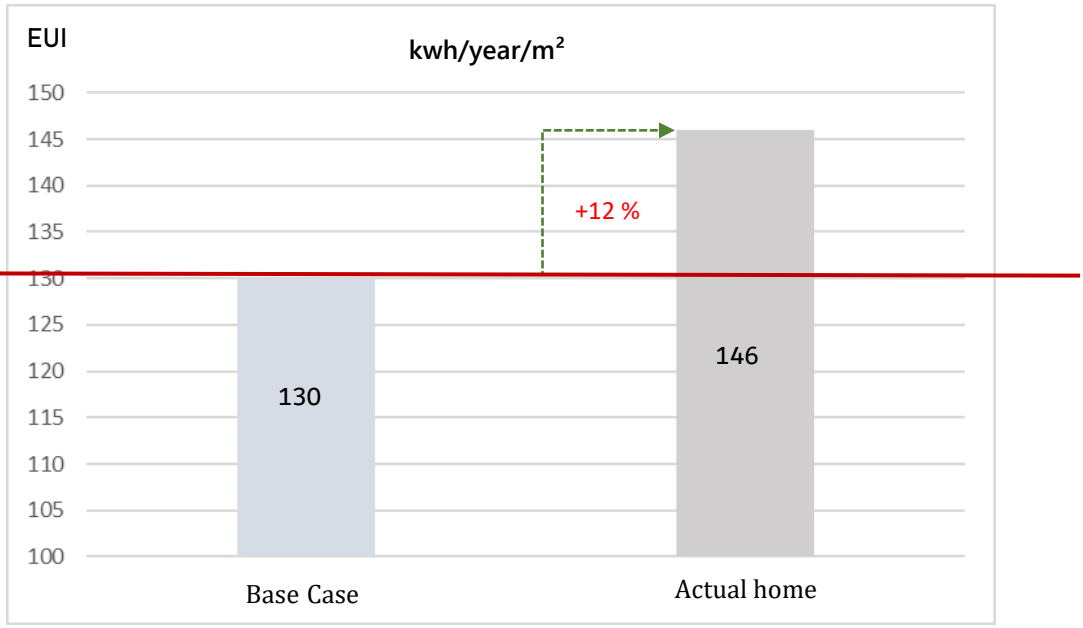


Figure 4.20 comparing the energy use intensity between the base case model and actual home in Dammam city.

4.6.3-Comparing the Base Case with Other Researcher Models

The other research model (Al-Saadi et al., 2007) that was chosen to compare with the base case was aimed at assessing the building envelope's thermal characteristics and determining those that enhance the energy efficiency of residential buildings in Saudi Arabia. This comparison assesses where the Base case stands regarding energy consumption compared to other research models. Al-Saadi et al. The model was simulated using the Visual DOE 4.1 energy simulation program employing Dammam and Riyadh

cities' weather files. In (Al-Saadi et al., 2007) model, Various envelope designs and four glazing types were considered. In (Saadi et al., 2007) study, there are more than fifteen models with different envelope specifications, and the most similar to the base case is design #7 (see table 4.17). The energy use intensity for the Al-Saadi et al. model is almost similar to the base case, with an increase of less than 1%. (See Figure 4.21).

Table 4. 17 compares specifications between the (Al-Saadi et al., 2007) model and the base case.

Parameter	Al-Saadi et al. Design #7 model	The Base case model
Location	Dammam city	Dammam city
Energy Simulation program	Visual DOE 4.1	IES
External wall U-Value (W /m ²K)	Design #7 U-Value (0.33 W /m ²K)	25mm stucco+250mm sandwich concrete block EPS filled core +25mm stucco (0.41W /m ²K)
Double-glazed window system U-Value (W/m²K)	The selected designs are evaluated under high-performance double glazing (U-value= 1.317 W /m ²K , SHGC= 0.278)	Openable double-glass windows (6mm/ gap/6mm) (1.25 W /m ²K)
Window-to-wall ratio (WWR)	20% of the gross wall area (98 m²),	8 % of the gross wall area (31 m²),
Roof U-Value (W /m ²K)	Design #7 U-Value (0.55 W /m ²K)	25mm terrazzo tiles+25mm mortar+ 4mm bitumen layer+ EPS 50 mm +150 mm cast concrete +25mm stucco (0.43 W /m ²K).
HVAC system	Residential System (Constant-Volume DX AC) with Electric Heating COP 2.87	Mini-Split Unit SEER of 3.6 & COP 3.49
Infiltration rate (ACH)	0.35 ACH	0.25 ACH
Simulation set-point (heating and cooling)	25ºC for Cooling, 21ºC for Heating	23ºC for Cooling, 19ºC for Heating
Equipment power density	12 W/m² (Ground Floor), 5 W/m² (1st Floor) 10 W/m² (Ground Floor), 8 W/m² (1st Floor)	Lighting: 1.6 W/ m², Refrigerating: 1.8W/ m², cooking: 12W/ m², misc.: 4W/ m² People: 90W/ person.
Lighting power density		
Energy use intensity (kWh/m²/year)	131 (kWh/m² /year)	130 (kWh/m² /year)

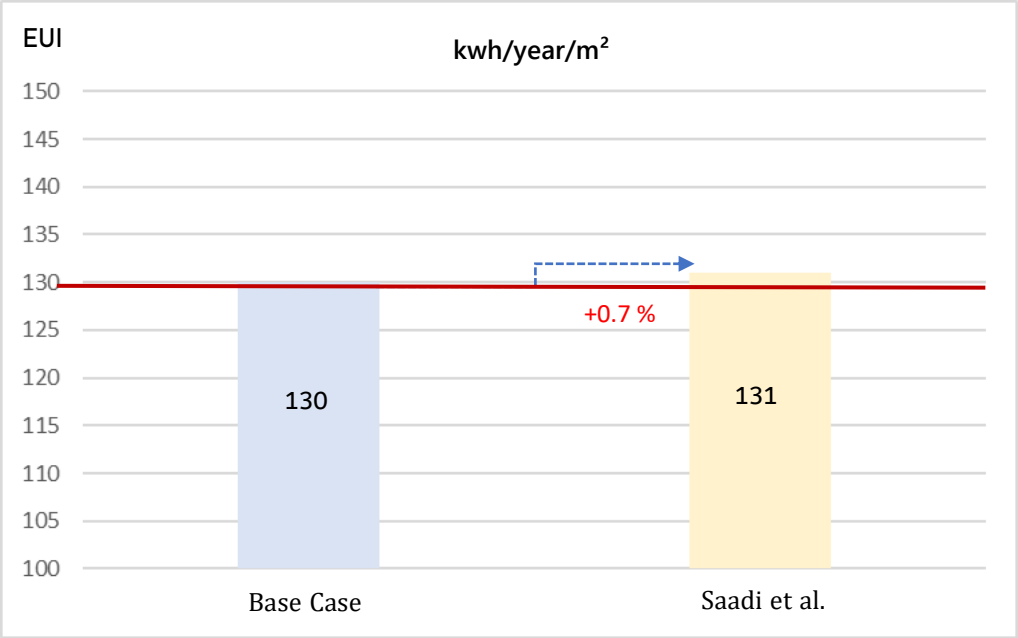


Figure 4. 21 compares the energy use intensity between the Saadi et al. model and the base case.

4.7- Summary

A mixed-method strategy, including qualitative and quantitative methodologies, is necessary for this investigation. The mixed-method process involves applying many research techniques, often including numerous phases that differ in their approaches and methods, to provide a more thorough synthesis of the study data analysis. On the other hand, in examining the base case's geometry and functional spaces, the south elevation is the most feasible orientation if the elevation is shaded with overhangs. The southern elevation can perform efficiently during the entire year. Yet, most of the projects that have been visited have no consideration for window shading. On the other hand, functional spaces have special and unique conditions regarding privacy levels and synthesis. The investigations showed that 35 % of the first floor is considered for guests, which is

unfeasible from a space utilization perspective. Nevertheless, 80% of the second-floor area is usually considered private since it contains all the house's bedrooms. Moreover, the "Sakana" program investigation revealed that the mean floor area for the residential buildings case studies reviewed in this chapter is 110-130 m². Furthermore, most houses have a garage with a 30-50 m² front yard. Nevertheless, a few case studies have a smallish backyard with around 15-25 m² area. Regarding the building envelope, most of the unit's external walls are constructed using thermally insulating blocks, and the roof has been sprayed with polystyrene that is compatible with Saudi code (SBC, 2018). On the other hand, double glass windows (6mm/thermal gap/6mm) are usually installed in the units' openings. Regarding the building envelope, In the NSAAG project, the roof is made of 30 cm flat slap reinforced concrete, while in the ASWAR project, the roof is made of a 35cm Ribbed. The concrete slab thickness is very beneficial for roof thermal insulation. The external walls consist of 40x20x20 cm sandwich concrete blocks, which are very handy for installation and satisfy the U-value requirements. Users' behaviour toward energy conservation plays a significant role in determining the total energy consumption. The occupancy operation schedule factors that influence the total home energy consumption and efficiency of building performance have yet to be investigated in depth in the research field. Most papers on the occupancy operation schedule in Saudi need to be updated. Nevertheless, according to the Dammam city residential survey, around 43% of users don't turn off their AC system when the room is unoccupied. Users' behaviour toward electricity use is an essential factor that helps decrease the EUI, which is around 182.4 kWh/m2 /year for the KSA East region. The precedent study validates the base case and Energy simulation tools that have been selected according to the NZEH requirements and future. The

validation process has been formulated in four main steps. After reviewing and analysing the most popular simulation tools in the market, eQuest and IES energy simulation tools were chosen to perform the study. Moreover, the base case has been compared with similar regional examples regarding construction specification and energy use intensity.

To validate the simulation tools selected in this research, a comparison was made between existing homes in Dammam city regarding the actual energy consumption and the predicted annual energy consumption for the same house using lES and eQuest energy simulation tools. The eQuest energy simulation tool prediction was 4% higher than the home's actual consumption. On the other hand, the IES simulation tool prediction was 1% less than the home's actual annual energy consumption. The minor tolerance in energy consumption percentage between both energy simulation programs could be due to several reasons. IES has more accurate results than eQuest energy simulation tools because it has more detailed building envelope profiles, especially cooling profiles, which tremendously affect annual energy consumption. Moreover, both programs have their weather file extension. Moreover, the Base case that has been made in the previous chapter has been validated by comparing it with the Dammam city's actual home energy use intensity. The result showed that the home selected in Dammam city has an energy use intensity 12% higher than the base case. This increase in EUI is because of the building envelope specification between the two houses

CHAPTER 5

Residential Buildings Survey Results

5.1-Introduction

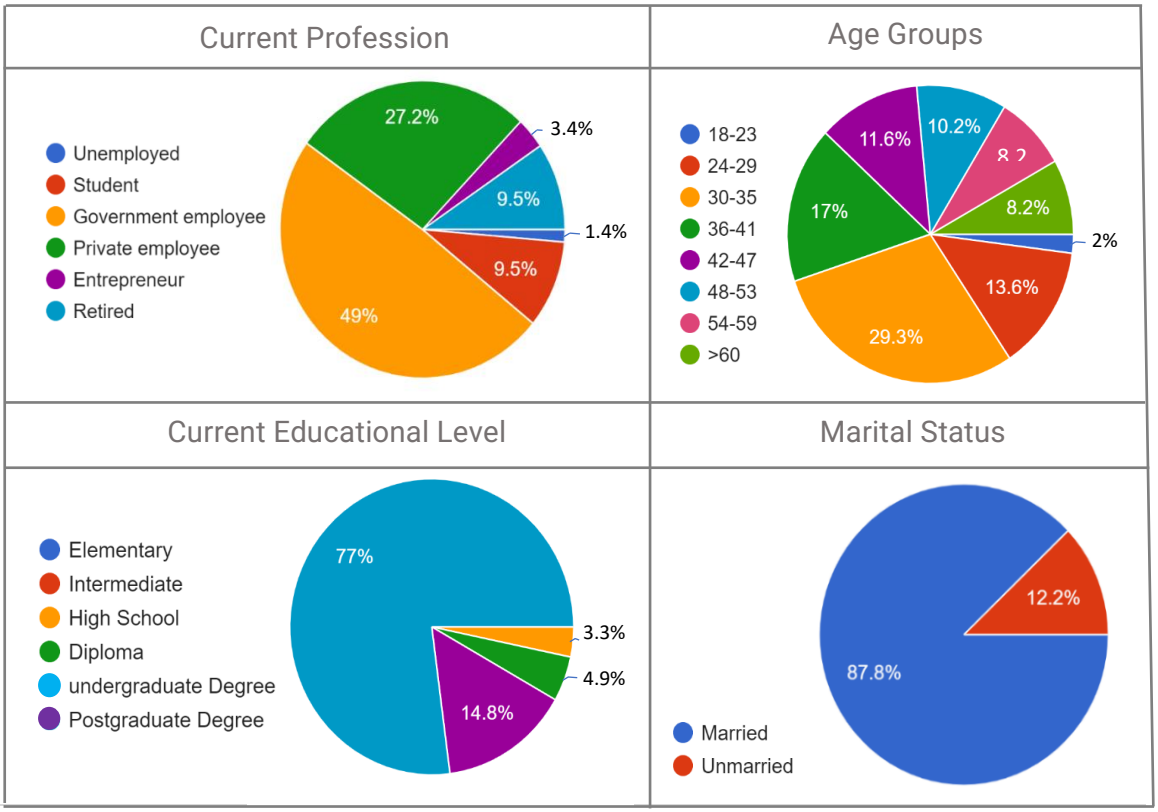
Implementing Net Zero Energy Homes (NZEHs) is a prosperous approach to enhance the energy efficiency and environmental sustainability of the residential sector in the region. Given the novelty of the NZEH concept in the region, assessing these residential residences' technical and economic feasibility is crucial (Maclay, 2014). This thesis investigates the feasibility of adopting Net Zero Energy Homes (NZEHs) in the region, focusing on technical and financial aspects. Understanding the architectural and residential building trends is crucial for determining residential energy consumption patterns in this society. The society is conservative regarding cultural and religious practices but also has an energy-affluent lifestyle due to highly subsidised energy prices in the region. All relevant parties must make concerted efforts to attain sustainable growth in the residential home industry. Specifically, experts in the construction business must embrace and advocate for sustainable building methods. Therefore, as explained in the methodology; to implement Net Zero Energy Homes (NZEHs) in the region, it is crucial to examine the comprehension and viewpoint of the individuals about sustainability. Investigating the occupants' perspectives about these new concepts is equally essential. As explained in the methodology previously, a study was created to specifically target the tenants of residential

properties to determine the architectural characteristics and construction systems of a typical house, as well as the inhabitants' perspectives towards sustainability and Zero Energy Homes (ZEHs).

5.2-Survey Demographics

In terms of profession, the survey showed that 50% of the participants are working in the governmental sector versus 27% in the private sector. On the other hand, the survey indicates that the percentage of unemployment between participants is 1.5% and the individuals working in their own business as an entrepreneur about 3.5%. Moreover, 65% of the participants are aged between 18-40 years old, and 8.2% are older than 60 years. Furthermore, 88% of the individuals are married versus 12 % are single. Regarding the education level, the survey showed that 90% of the individuals hold a university degree, and 15% of them hold a postgraduate degree (see table 5.1).

Table 5. 1 Survey demographical statistics including profession, age, education, and marital status.



The survey showed that 65% of the group aged between 24 and 29 are married, and 85% of the participants aged above 30 are married (see Figure 5.2).

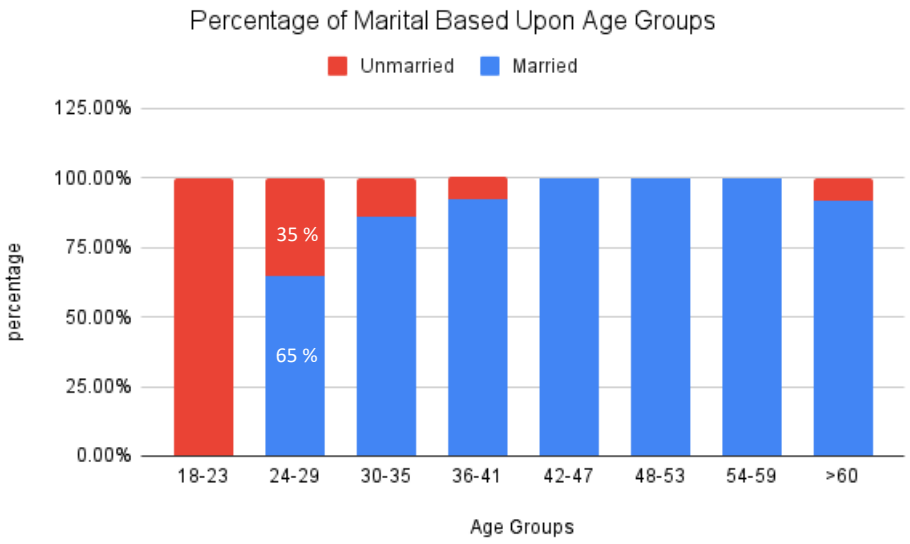


Figure 5. 2 The percentage of marital status based upon age groups.

Further analysis indicated that the average family size tends to decrease with the increment in individuals' education level (Inverse Relationship). Moreover, The minimum family size is two, and the maximum is ten, with a mean family size number of six members (see Figure 5.3).

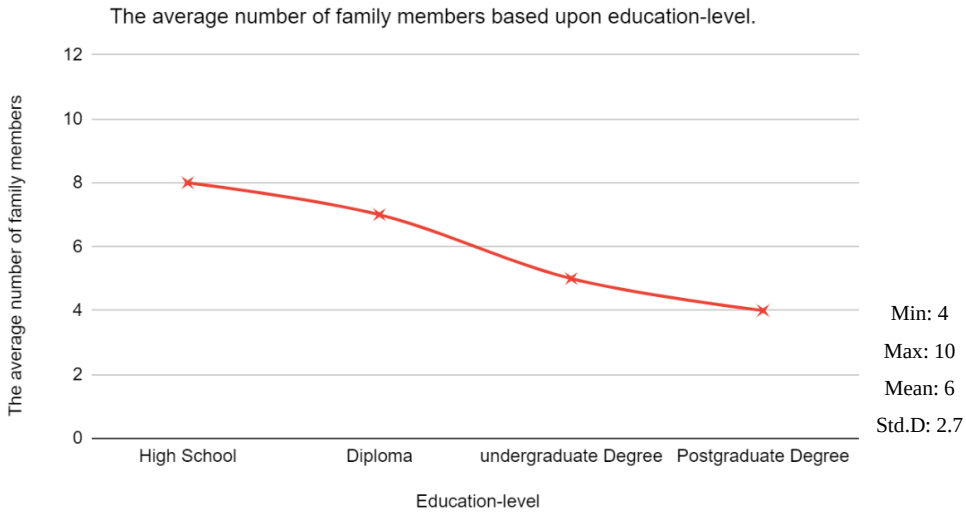


Figure 5. 3 The average size of family member based upon education level.

5.3-Residential buildings condition

In response to questions about the current home type, about 41.7 % of participants live in apartments, and more than 46 % have selected villas as their current residence type (see Figure 5.4). Moreover, the survey showed that 50 % of the individuals live in a home floor area less than 400 m², and the mean of the home floor area in Dammam city was 492 m² (see Figure 5.5).

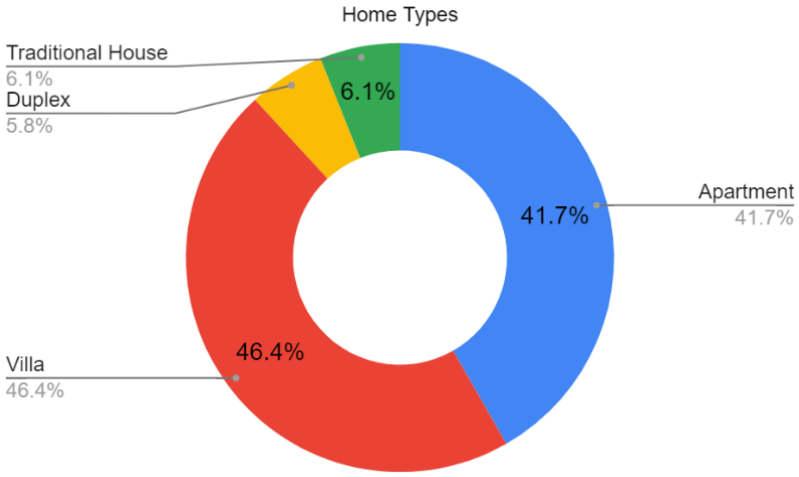


Figure 5. 4 Residential building types and the percentage of current building types.

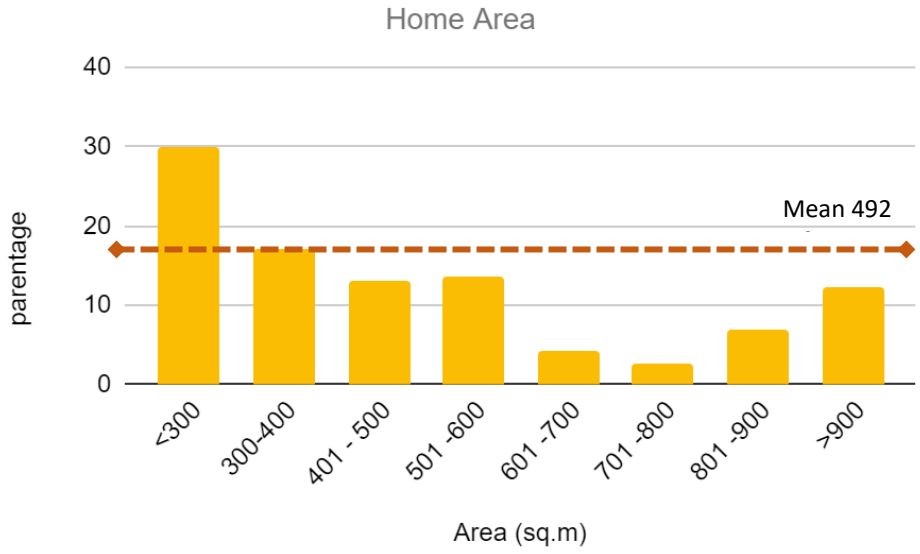


Figure 5. 5 Residential building floor area and the percentage of each area groups.

Regarding residential buildings contract type, the survey revealed that 57.5% of the participants owned their homes versus 35% of them rented their homes. The increase in the percentage of owning homes in Saudi Arabia, in general, is due to the governmental, residential buildings supporting programs, and governmental financial loans (GASTAT, 2019).

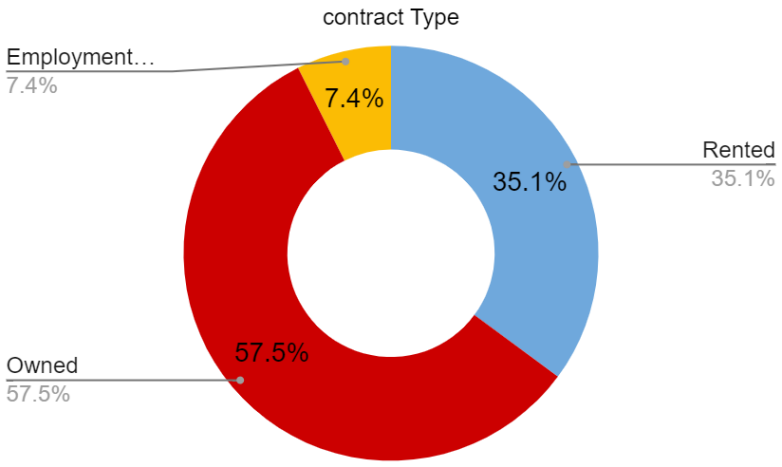


Figure 5. 6 Residential building contract types and the percentage of each type.

On the other hand, the results showed that about 80% of the participants' current dwellings were built within the last three decades. Moreover, the survey showed that the mean construction period for the existing buildings was between 1998 and 2008 (see Figure 5.7).

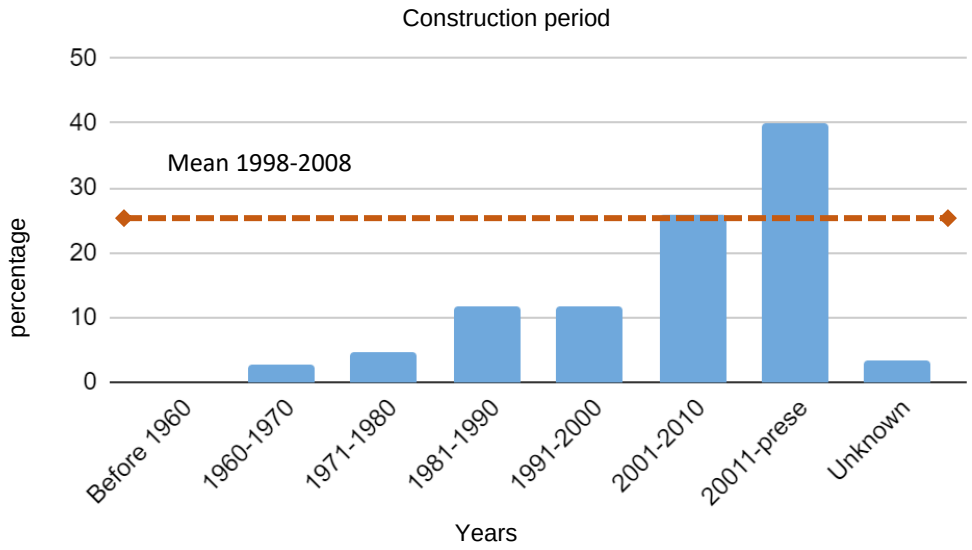


Figure 5. 7 Residential buildings Construction periods and the percentage of each period.

Regarding the finance source for current residential homes, the result showed that finance income mainly was from savings, loans, or a combination of these two with a percentage of 64% (see Figure 5.8). However, about 37% of participants don't own a home and pay their monthly home rent.

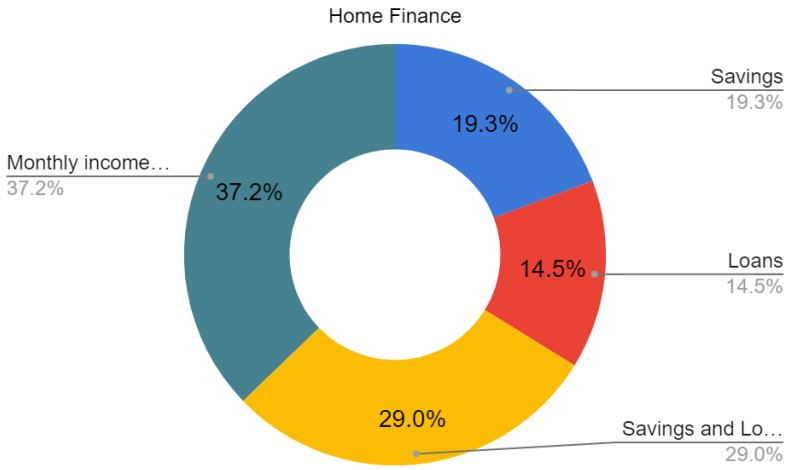


Figure 5. 8 Residential buildings home finance method.

5.3.1- Type and Number of Floors & Internal Spaces

This survey is also concerned with identifying the type and number of internal spaces for current residential buildings. In this consideration, participants were asked about 16 of the most common functional spaces utilized in Saudi residences. Figure 5.9 summarizes the number of each space used in participants' current residences and the Min., Max., and Mean spaces numbers for each function. Furthermore, the results revealed that there are some functional spaces that have a mean number less than 0.5, which indicates that those spaces are not widely in use, such as external kitchen, office, and Annex room. On the other hand, the mean number for some common functional spaces such as bedroom, bathroom, and living room is 3, 2.7, 1.5, respectively.

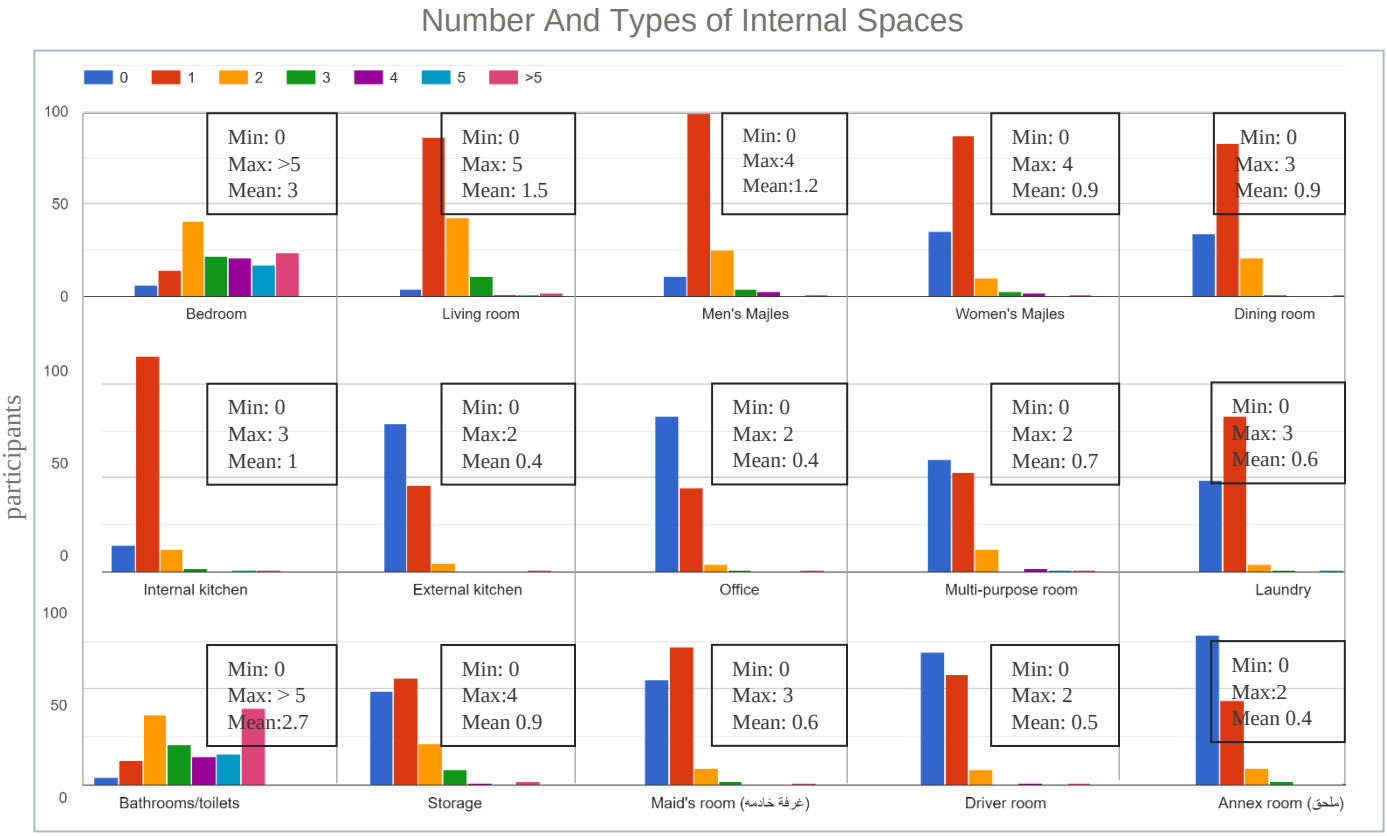


Figure 5. 9 Number and type of internal spaces showing the Min., Max., mean of each space.

The results also showed that the mean for all types of current residential buildings floor was found to be two floors. Nevertheless, around 25% of the participants have reported living on three floors of residence (see Figure 5.10).

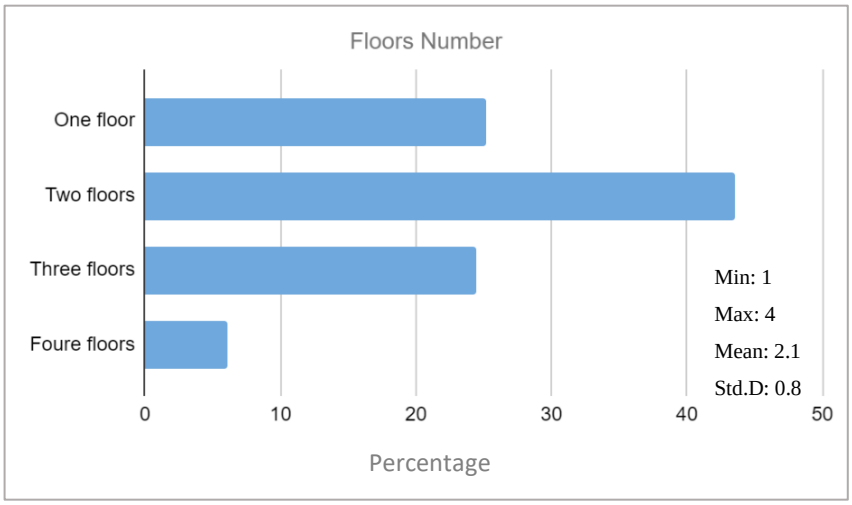


Figure 5. 10 Number and percentage of residential building floors showing the Min., Max., mean and Std D.

5.3.2- Type of Cooling, Heating, and Artificial Lighting Systems

The survey also endeavored to define the building systems used for cooling, heating, and lighting. In this respect, participants were asked about the type of systems employed in their current residence. Moreover, some questions regarding the individual's consumption behavior were asked to identify how users behave toward energy conservation. Regarding building cooling, the results revealed that the majority of the participants, about 73.5 %, use a split unit system. Furthermore, around 40% of individuals use a window-type air conditioning (AC) system (a conventional A/C unit fixed in a window frame through the walls**)** (see Figure 5.11).

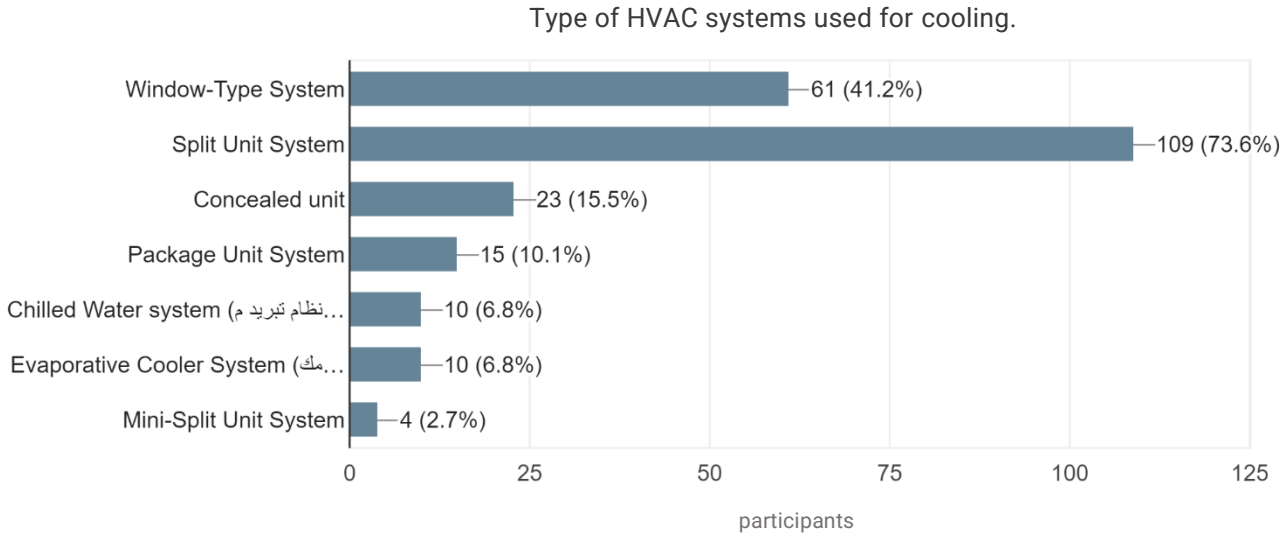


Figure 5. 11 The HVAC systems typically used for cooling and the percentage reported for each type.

Furthermore, 152 of the participants have reported their air condition thermostat setback point with a Min. 18 ºC, Max. 26 ºC, mean 23 ºC (see Figure 5.11). Moreover, more than half of the individual’s setback their thermostats between (23 ºC - 24 ºC), and the standard deviation for the thermostat setback point was 1.57 ºC which indicates that the thermal comfort for the participants is scattered closely around the mean.

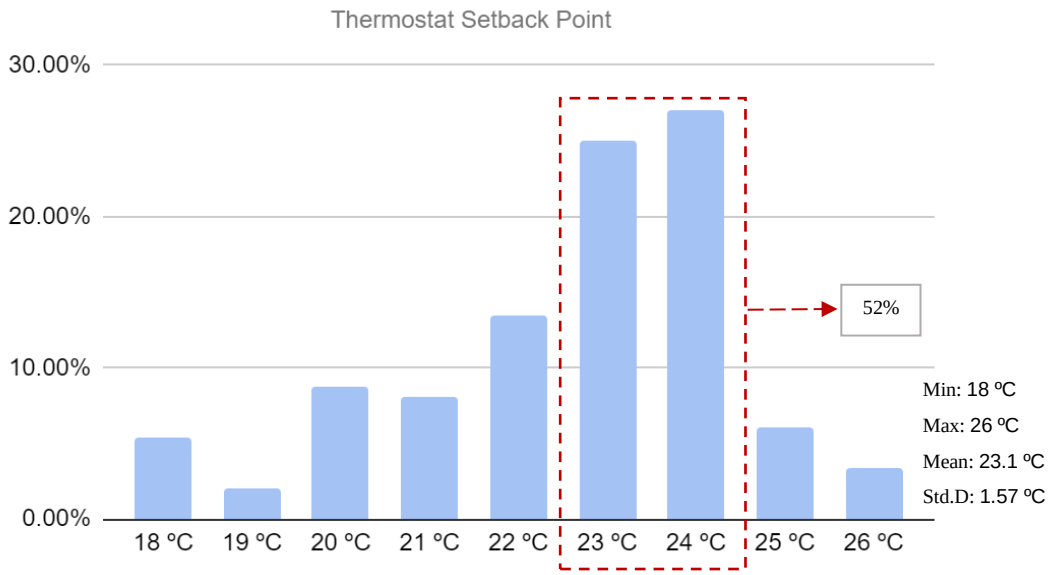


Figure 5. 12 Air conditioning thermostat setback points and the percentage reported for each point.

In order to measure how users behave toward HVAC system energy conservation, participants were asked if they turn off their AC system when the room is unoccupied. Extraordinarily, 19% of the users don't turn their AC system off even when the room is unoccupied. On the other hand, 55% of the participants reported that they do turn the AC system off when they go to work (see Figure 5.13).

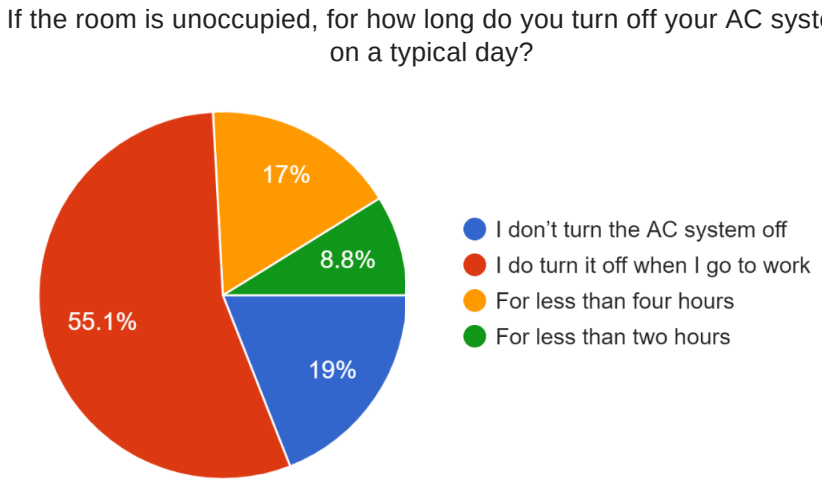


Figure 5. 13 how users behave toward HVAC system energy conservation.

Regarding the heating system, the results showed that 30 % of participants do not need any heating systems in their current home during winter; nevertheless, the majority tends to use oil-filled radiators and halogen heating devices in their existing residences (see Figure 5.14).

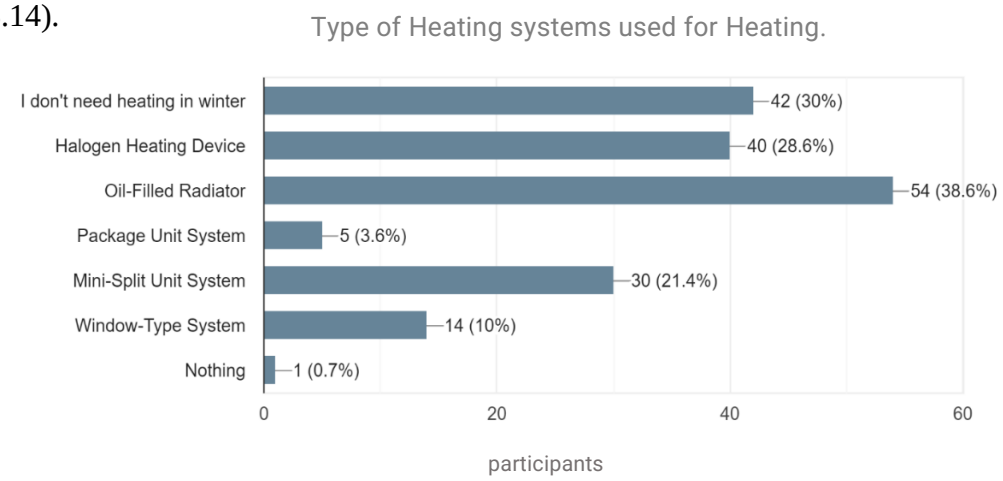


Figure 5. 14 HVAC systems typically used for heating and the percentage reported for each type.

Currently, Saudi residences are fitted with lighting fixtures in terms of artificial lights, including incandescent, tubular fluorescent, compact fluorescent lamps, LED, and tungsten-halogen lamps. Among these fixtures, LED tends to be the existing most common option between participants with a percentage of around 70% (see Figure 5.15).

.

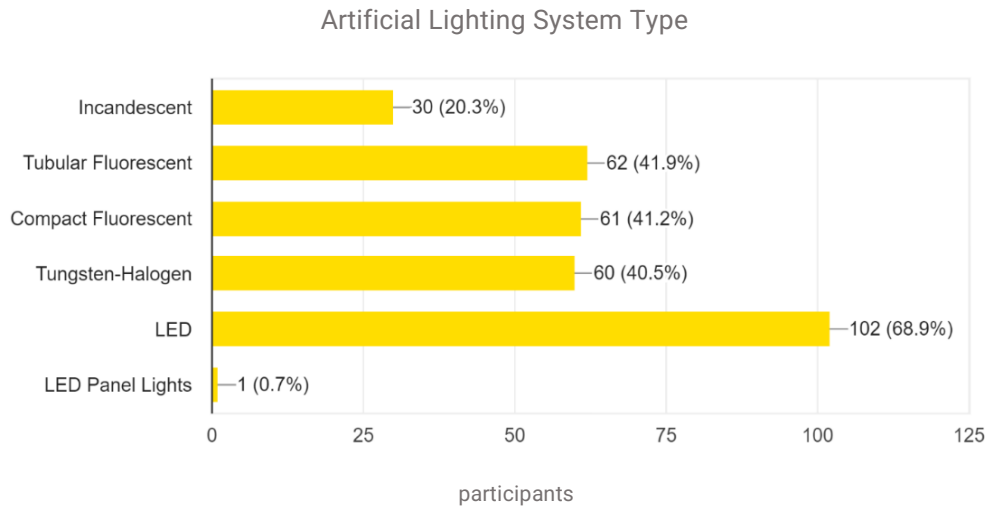


Figure 5. 15 Artificial lighting systems typically used in homes and the percentage reported for each type.

Regarding domestic buildings' water heaters, the survey has shown that separated indoor units are the most desirable system in a domestic building with around 75%. On the other hand, an instant water heating system wasn't popular in democratic buildings. In fact, the survey indicates that only 2.8% of the participants reported using the instant water system (see Figure 5.16).

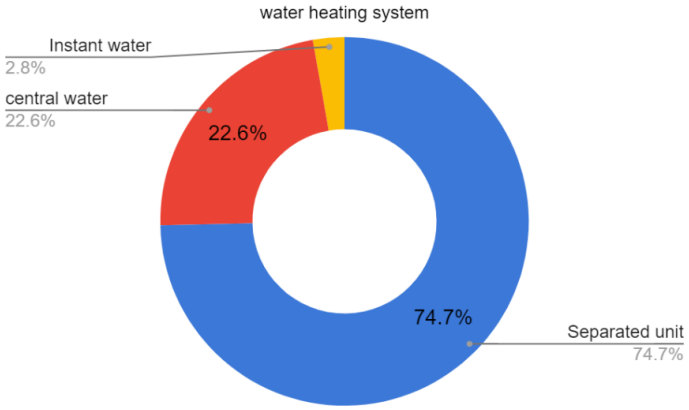


Figure 5. 16 Water heating systems and the percentage reported for each type.

Moreover, For the sake of measuring how users behave toward energy conservation regarding water heating systems, participants were asked if they turn off their water heating system in summer. Extraordinarily, 18.7% of the users don't turn their water heating system in summer. On the other hand, around 60% of the participants reported that they don't need water heating in summer at all (see Figure 5.17).

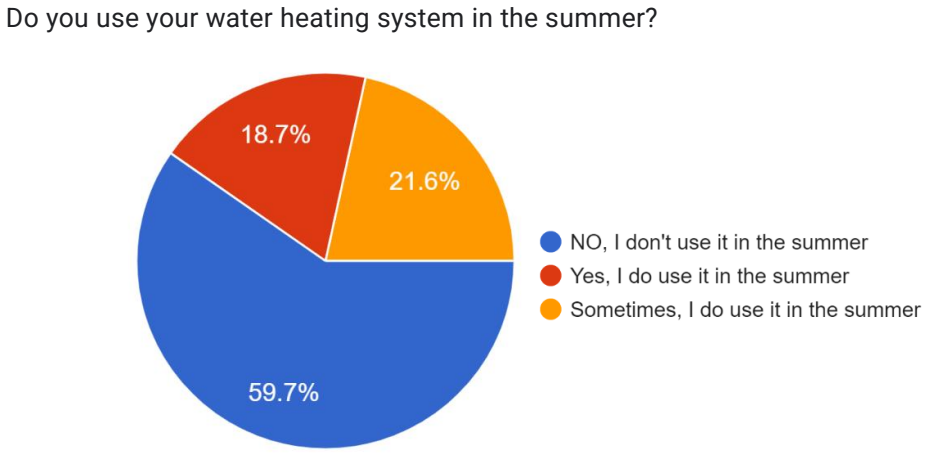
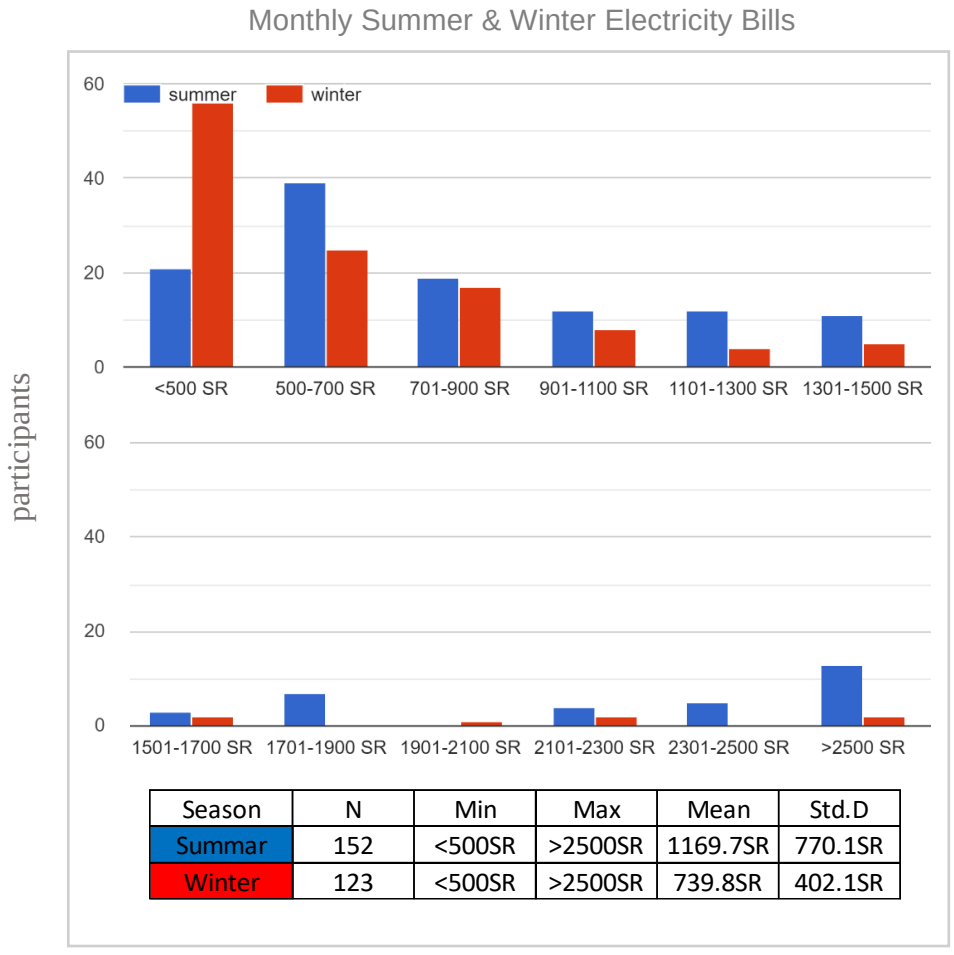


Figure 5. 17 How users behave toward water heating system energy conservation.

5.3.3- Summer & Winter Electricity Bills

In terms of the electricity bills, around 152 participants have reported their summer and winter electricity bills, the mean for the bills in the summer is 1170 SR and 740 SR for the winter. Moreover, the standard division for the summer bills is 770 SR. Furthermore, around 50% of the participants receive a summer electricity bill with an average of less than 500SR. Coupled with, new Electricity Tariffs for all building types as approved by the Council of Ministers' Decree dated 12/12/2017, which has been applied since 1/1/2018 (SEC, 2018), the estimated energy consumption bills converted from cost (SR) to consumption (kw/h) is with a mean of 4680 kw/h in summer and 2960 kw/h in the winter (see Figure 5.18).



Season	N	Min	Max	Mean	Std.D
Summar	152	<500SR	>2500SR	1169.7SR	770.1SR
Winter	123	<500SR	>2500SR	739.8SR	402.1SR

Figure 5. 18 Average monthly summer & winter electricity bills.

5.3.4- Building Envelope

One of the significant factors investigated in the survey regarding residential buildings is the building envelope. In this respect, Participants were asked about the building envelope and window glazing types at their existing residences. The results have shown that the Insulated concrete block (Sandwich Block) was the dominant wall construction type in the participant residence. Nevertheless, there were uninsulated building envelope residences with 21 %. Moreover, 25% of the participants have noted that they don't know their envelope construction type (see Figure 5.19).

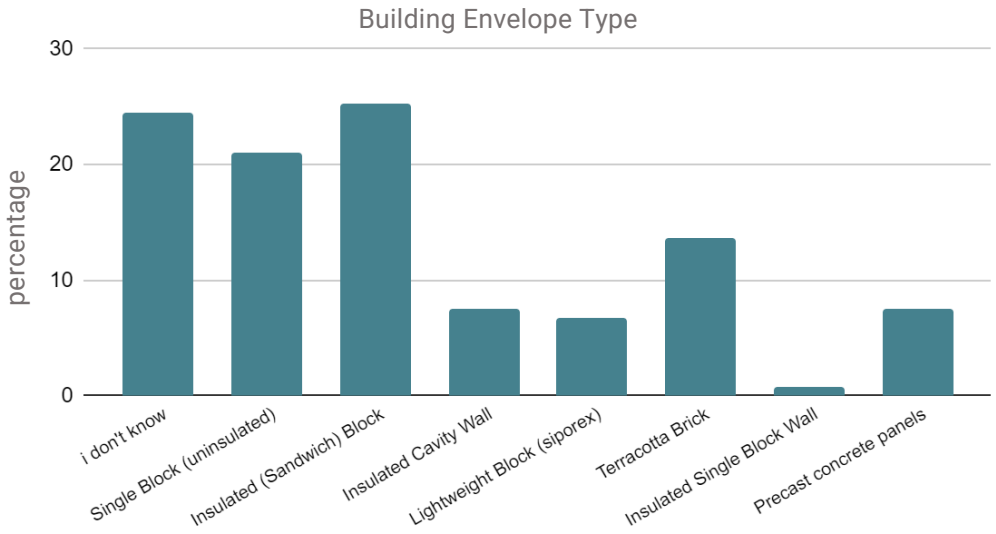


Figure 5. 19 Building construction systems typically used in the Saudi market and the percentage reported for each type.

Window glazing type is another important factor in Building envelope; participants have reported using the single and double-glazing type with a percentage around 31%, 44% respectively. On the other hand, 24.5% of the individuals don’t know their glazing type.

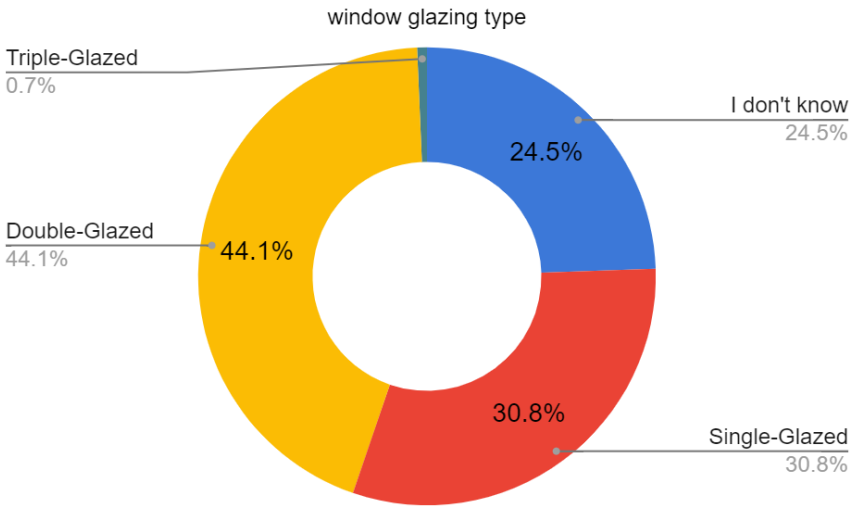


Figure 5. 20 Windows glazing type and the percentage reported for each type.

5.4-Views Towards the Application of ZEHs In Dammam City

Since the proposed prototype will engage the idea of applying ZEHs in Dammam city, it was essential to explore the Dammam city residents' views toward energy conservation in general and ZEHs in particular. Given that the concept of ZEHs is relatively new to Saudi residents in general, the survey questions were kept simplified and written in common terminology. In his regards, participants were asked questions about the fact that Net-Zero-Energy-Houses cost more initial price than a traditional house, so to what extent do they accept paying more initial price if they get the tolerance back in a specific payback period due to electricity bills saving. Remarkably, around 95 % of the participants don't mind the idea of paying for a Net-Zero-Energy-House in the future, and 32% consider the idea as highly acceptable. Nevertheless, 5% of the individuals have reported that they don't like the idea of NZEHs (see Figure 5.21).

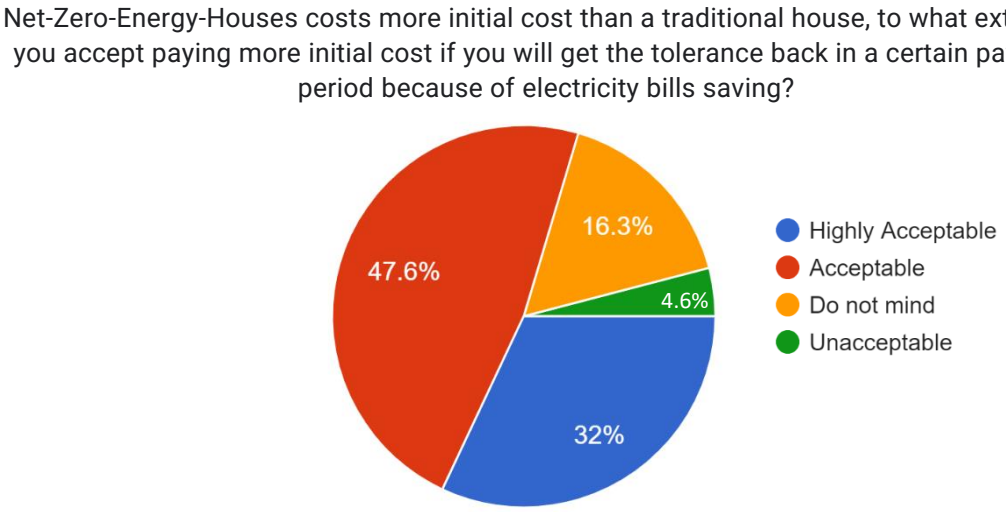


Figure 5. 21 Measuring the acceptance of applying the idea of NZEHs in Dammam city.

Moreover, this survey also attempted to investigate the participants' awareness regarding the energy rating of their household HVAC system and appliances. The results indicated that more than 20% are not aware of all the energy rating cards of their household appliances and HVAC system, and 30% are knowledgeable about all of them; furthermore, around half of the participants are aware of some of their rating systems cards (see Figure 5.22).

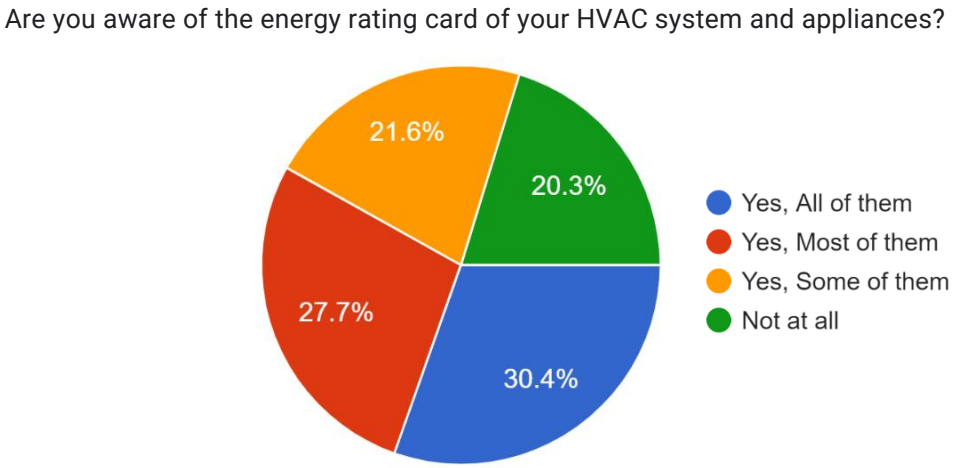


Figure 5. 22 Measuring the awareness of energy rating cards for HVAC systems and appliances.

5.4.1-Views Towards Applying Energy Efficient Measures

The survey intended to examine the acceptability of sustainable design and energy-efficient measures to investigate the views towards ZEHs in Dammam City from residents' perspectives. Previously, participants were asked about their acceptability of paying more for buying an environmentally friendly residence. The results demonstrated that participants are happy to pay more for constructing or purchasing a sustainable home. After that, based upon a four-point evaluation scale, examining five energy-efficient measures, participants were asked to check their acceptability towards the concept of sustainable design and EFMs. The result has shown that photovoltaic panels and courtyards were the most attractive measures, With acceptance from 95% of the participants. On the other hand, a micro wind turbine was the most undesirable measure since 65% of participants didn't like the idea of having a wind turbine on the top of their residential roof. Moreover, in the opposite of what the literature reviews indicate, around 85% of the participants don't mind the idea of having a green roof at the top of their residence (see Figure 5.23).

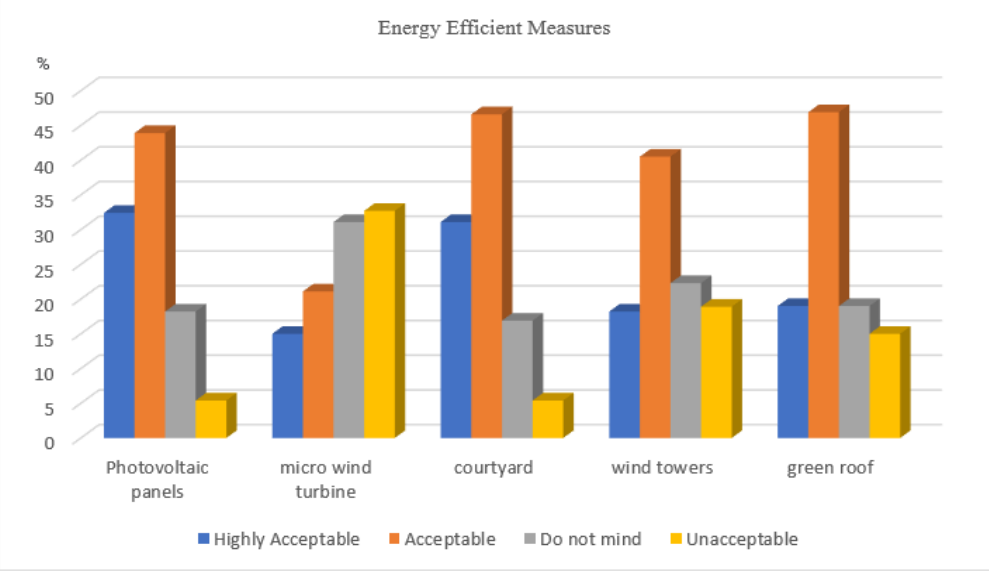


Figure 5.23 Examine the acceptability of sustainable design and energy-efficient measures to investigate the views towards ZEHs.

5.5- Remarks

According to the survey, around 65 percent of the participants are between 18 and 40, making implementing new design concepts more acceptable among the younger generation and focusing on the relatively younger segment of society that needs to construct new homes. Moreover, the survey results and findings help us understand the demographical distribution in Dammam city. Regarding the education level, the survey showed that 90% of the individuals hold a university degree, and 15% of them hold a postgraduate degree. Subsequently, since most participants have an academic background, around 95 % of them do not mind the idea of paying for a Net-Zero-Energy-House in the future. Further analysis indicated that the average family size tends to decrease with the increment in individuals' education level (Inverse Relationship). Moreover, The minimum family size was two, and the maximum was ten, with a mean family size of six members. Henceforward, the elevated mean of the family size members in Dammam city explains the high mean of the home floor area, which was around 492 m^2. Regarding the residential building evaluation, the trend now in Saudi Arabia, in general, is to own a diminutive-sized villa or duplex financed by the government, residential building supporting programs, and governmental financial loans (GASTAT, 2019). In terms of Cooling, Heating, and Artificial Lighting Systems, the results revealed that most of the participants, about 73.5 %, use a split unit system for cooling. Moreover, the mean for the thermostat's setback point was 23 ºC with a standard deviation of 1.57 ºC, indicating that the participants' thermal comfort is scattered closely around the mean. (See Table 5. 2) which summaries survey findings and illustrates some remarks.

Table 5. 2 illustrations of the survey findings and remarks.

Survey divisions		Survey findings		Remarks
Buildings Systems 	Cooling	▪ most of the participants, about 73.5 %, use a split unit system.		✓ the standard deviation for the thermostat setback point was 1.57 ºC which indicates that the thermal comfort for the participants is scattered closely around the mean. ✓ 19% of the users don't turn their AC system off even when the room is unoccupied, and 18.7% of the users don't turn their water heating system in summer. ✓ Sandwich Block doesn't consider the ultimate choice regarding thermal insulation compared to continuous board insulation because of the thermal bridging disadvantages.
	Heating	▪ 67% of participants tends to use oil-filled radiators and halogen heating devices.		
	Lighting	▪ LED is the most common option between participants with a percentage of 70%.		
	Water Heating	▪ separated indoor units are the most desirable water heating system with around 75%.		
	Envelope	▪ Insulated (Sandwich Block) was the dominant wall construction type in the participant residence.		
	Glazing	▪ participants have reported using the double-glazing type with a percentage of around 44%.		
		▪ 152 of the participants have reported their air condition thermostat setback point with a mean of 23 ºC. ▪ 30 % of participants do not need any heating systems at their current home during winter. ▪ The mean for the electricity bills in the summer was 1170 SR with a consumption of 4680 kw/h/month and 740 SR in the winter with 2960 kw/h/month. Subsequently, the mean for the annual home energy consumption is around 50,000 kw/h/year.		
NZEHs Views 	Solare P.	▪ As a dominant EEMs, The result has shown that photovoltaic panels and courtyards with a fountain were the most attractive measures, With acceptance from 95% of the participants.		✓ in the opposite of what the literature reviews indicate, around 85% of the participants don't mind the idea of having a green roof at the top of their residence. ✓ around 65 percent of the participants are between the ages of 18 and 40 and 90% of the individuals hold a university degree, making the idea of implementing new design concepts more acceptable among the younger generation and focusing on the relatively younger segment of society that needs to construct new homes.
	Court Y.			
	Wind Ct.	▪ Wind catcher wasn't a desirable choice among the participants with just acceptance from 55%.		
	Green R.	▪ Only 15% of the participants like the idea of having a green roof at the top of their homes.		
	Wind T.	▪ Only 35 % of the participants liked the idea of having a wind turbine on top of their residents.		
	NZEH	▪ 95 % of the participants don't mind the idea of paying a Net-Zero-Energy-House in the future.		

5.6- Summary

The drive of this study was to determine the architectural characteristics of a typical home in Dammam, Saudi Arabia, in terms of type, size, building systems, and individual energy consumption. It also attempted to determine how Saudi occupants sensed sustainability and ZEHs in general. The concept of NZEHs is new to Saudi residents. Nevertheless, the concept of sustainable residences, in general, is appealing to residents, and most are willing to spend more to buy or construct their own sustainable homes. Remarkably, around 95 % of the participants do not mind paying for a Net-Zero-Energy-House in the future, even though it might cost them more than a conventional home. Furthermore, achieving ZEHs relies on combining multiple principles, including passive design features, energy-efficiency measures, and renewable energy applications. The result showed that photovoltaic panels and courtyards were attractive measures, with acceptance from 95% of the participants.

Ultimately, this research has contributed to the effort to identify the architectural features of a typical residence, including its design features, building systems, and tenants' energy behavior. It also aimed to ascertain residents' general perceptions of sustainability and Zero Energy Homes (ZEHs). This survey research had a few limitations, including the fact that the survey distribution occurred in 2021 during the COVID-19 pandemic period when physical interaction was constrained and restricted. On the other hand, Another factor was the use of technical NZEH terminology, which was not understood by the general population. In addition, some applicants lacked enthusiasm when answering questions related to the house specification section since it included technical language.

CHAPTER 6

Design And Conceptualization of the Net Zero Energy House (NZEH)

6.1-Introduction

As the sequence of conducting the data and investigating the technical and economic viability in the path toward developing the Net-Zero-Energy prototype, the research started by exploring local vernacular architecture and passive cooling techniques, coupled with investigating the energy efficiency measures which are suitable for our regional hot and humid climate, moreover, previous researchers' models in the field of NZEHs were explored and examined to Evaluate the base case performance using other researcher models as a benchmark for construction specification, data parameters, and total energy use intensity (EUI). Moreover, this step estimates where the Base case's energy consumption corresponds to other research models. Data was collected in Dammam city to gather the base case information by conducting surveys, project site visits, and interviews. The data collection stage helped design the Dammam city base case, which has been modelled and simulated using the energy-stimulating program IES and eQuest. The designed base case was validated by comparing the simulated model data with other regional researcher models (see Appendix D). In this chapter, the designed base case will be developed by involving passive cooling techniques and energy-efficient measures to reach the energy-efficient stage; after that, renewable energy applications will be applied to achieve the NZE stage. Moreover, in this stage, a framework and suggestions will be

made to set up the best combination for both the measures and renewable energy applications in terms of cost and efficiency.

6.2-Designing The Net Zero Energy Home (NZEH)

In the previous data collections, it has been recognized that homes in Saudi have higher electricity consumption demand than the international standard. Consequently, to develop ZEHs in Dammam City, it is essential to decrease the electricity consumption for the conventional home first before applying renewable energy applications. This can be fulfilled by employing sustainable design features and increasing the base model's energy efficiency through energy-efficiency measures. In this examination, as (figure 6.1) shows, the ZEH designing process is broken down into three main phases: the potential of saving energy, NZEH Decision-Making development, and NZEH prototype Final design.

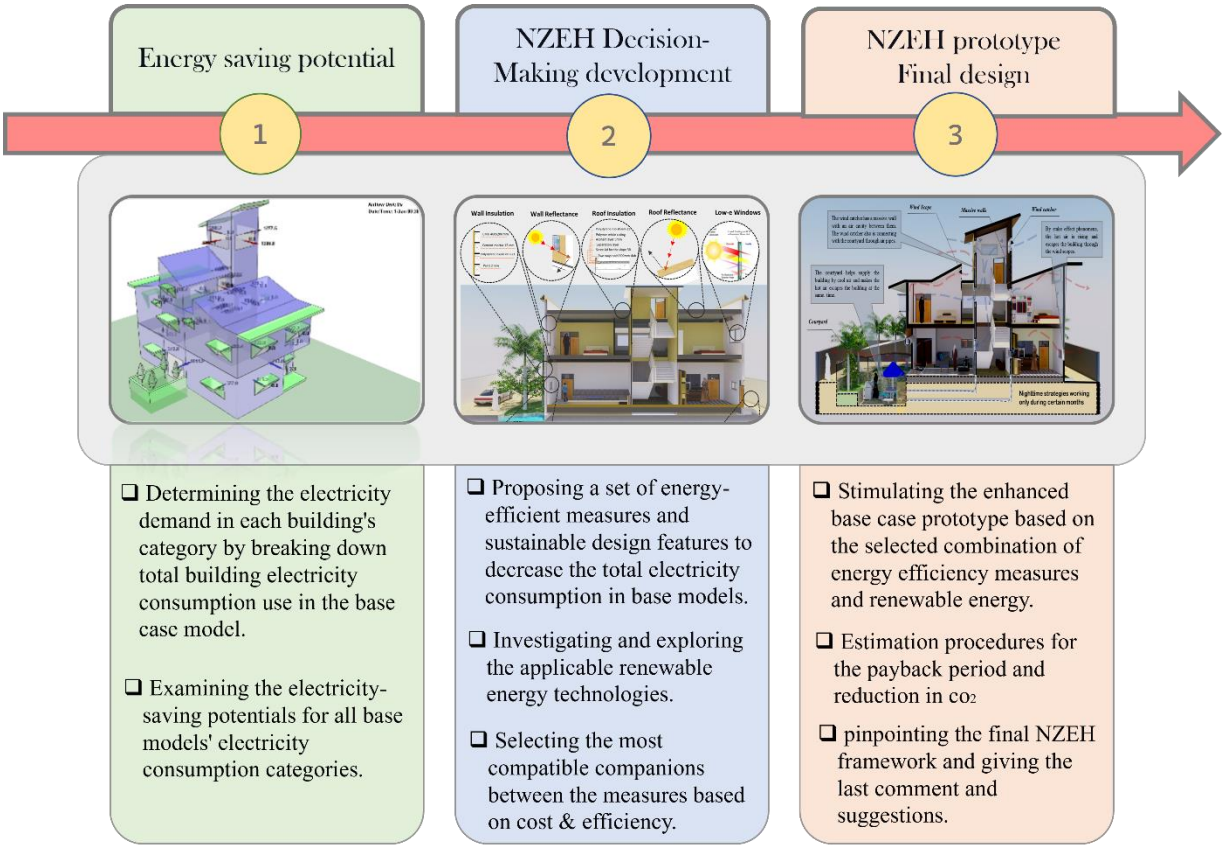


Figure 6. 1 NZEH designing stages, which has been broken down into three main phases.

6.2.1- The potential of saving energy

The base case must be diagnosed to determine energy consumption in each building service category to ensure the optimum selection for energy-efficient measures. Moreover, estimating the potential of saving energy from the original base case during the base case diagnosis process is essential to ensure that the enhancement process will be feasible. A breakdown analysis of the base case total energy consumption indicates that the electricity demand notably comes from four primary categories, heating, ventilation, air-conditioning (HVAC) system, domestic equipment (including cooking and refrigerating), lighting, and water heating.

After the analysis, the HVAC system is the dominant electricity consumer among all base-case building systems, consuming 51% of the home's total energy. On the other hand, DHW, refrigerating, and cooking consume 15%,10%, and 5% of total energy consumption (see Figure 6.2).

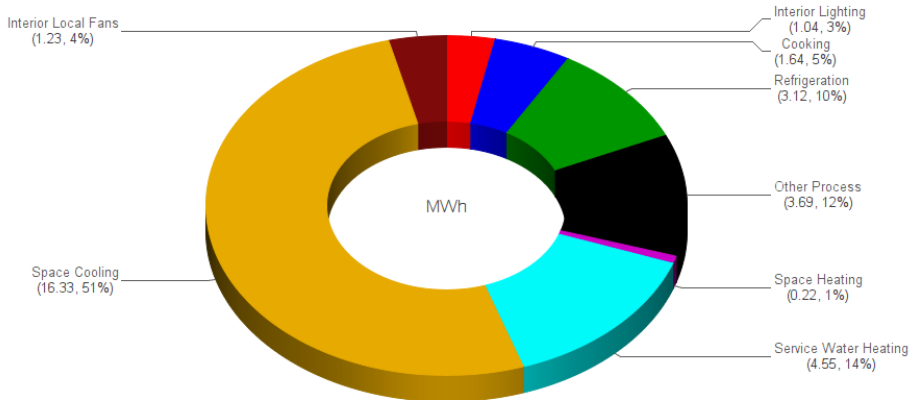


Figure 6. 2 IES diagram for base case energy consumption in each building service category

To investigate the HVAC system's high energy consumption, heat gain resources, both (internal and external), must be diagnosed since it's considered the primary contributor to the cooling load. In the base case, internal heat gain resources contribute to the cooling load by 54% versus 39% for external heat gain (see Figure 6.3).

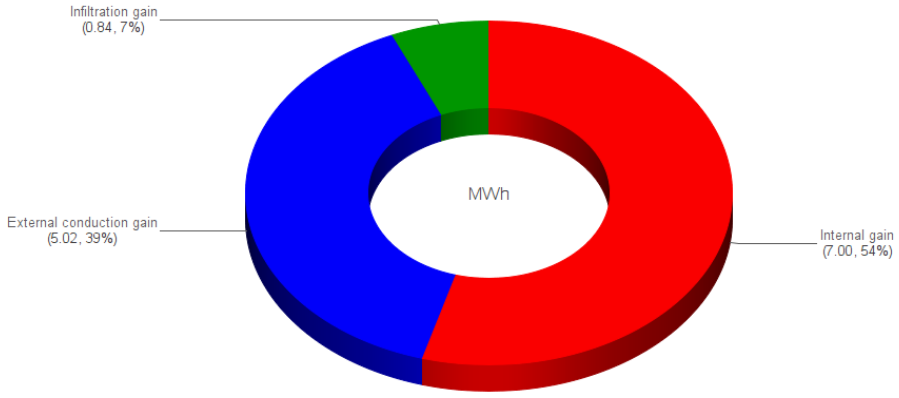


Figure 6. 3 IES diagram for base case primary heat gains resources that affects the HVAC load.

Further breaking down to the external heat gain resources revealed that External conduction occurs through the building envelope, including walls, roof, windows, and doors. The examination indicated that the impact of each component on the external conduction gain directly correlates with the envelope surface area subjected to the sun. Walls are marked to be the most influencing external contributor to the HVAC loads, with an external heat gain of 62%. The roof is the second contributor, with a 25% heat gain. On the other hand, exterior windows and doors contribute to the heat gain with 9% and 5%, respectively (see Figure 6.4).

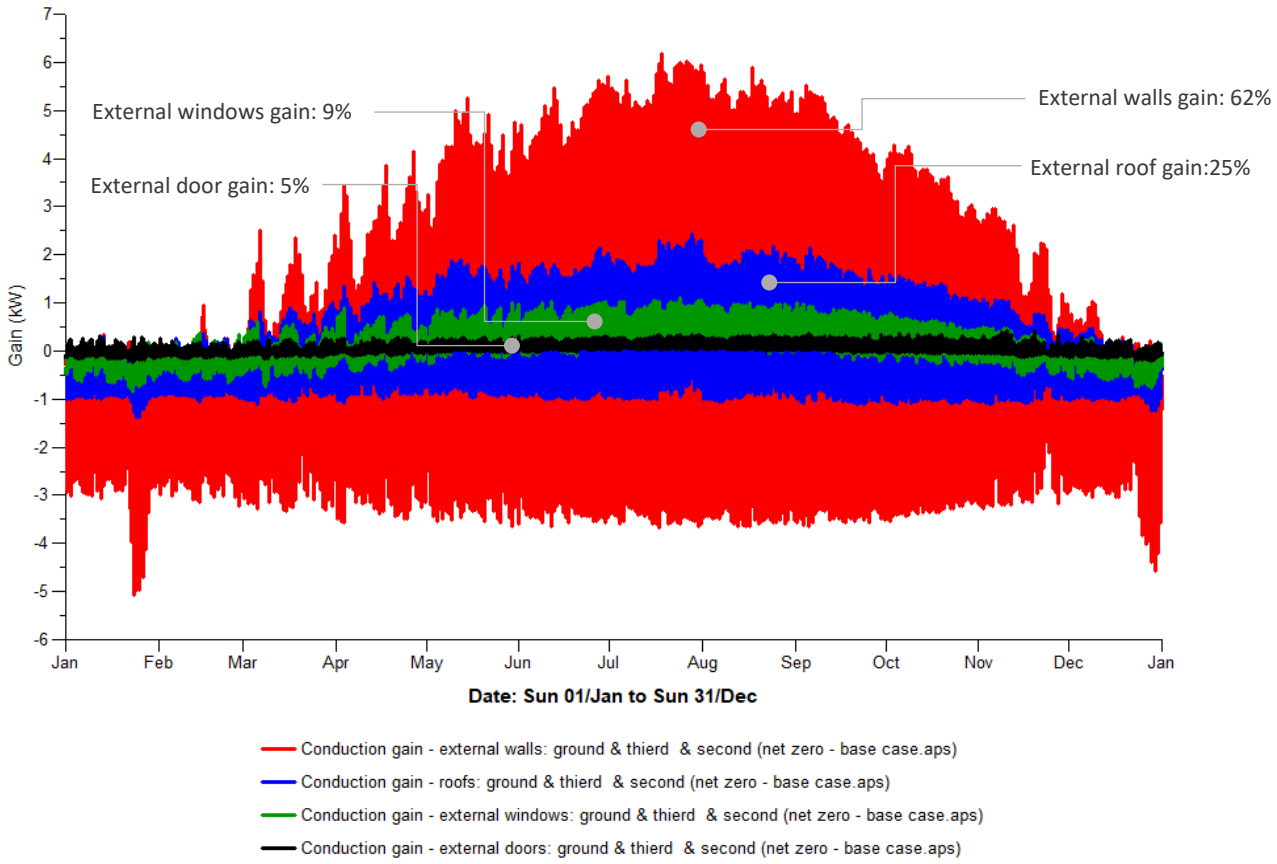


Figure 6.4 IES chart for base case primary external heat gain resources

Interior conduction usually occurs from resources inside the home, including people, equipment, lighting, and thermal mass from the ground floor. The investigation showed that people are observed to be the most contributor to the HVAC loads, with an interior heat gain of 60%. The heat gained from people usually depends on the number of people living in the home and the type of activities during the day. Equipment is assumed to be the second benefactor, with a 19% heat gain (see Figure 6.5).

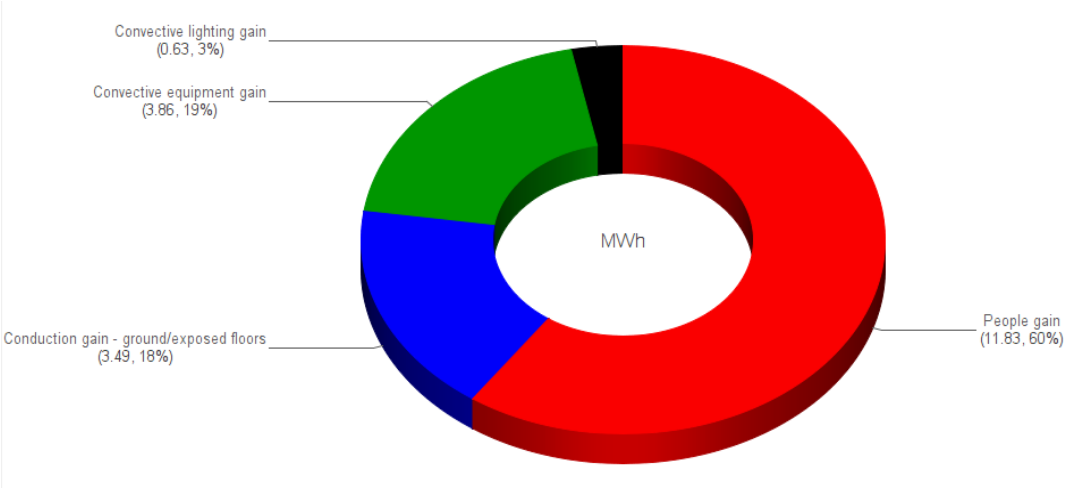


Figure 6. 5 IES diagram for base case primary internal heat gain resources

As the base case energy consumption investigation showed, the HVAC system consumes half the total building energy demand. Moreover, since 64% of the external heat gain comes from walls, the exterior wall heat gain is the primary resource that increases the HVAC system's electricity load. So, during the base case enhancement process, a deep look into the HVAC system efficiency and the building envelope components is essential to target the most building energy consumption factors.

On the other hand, a sensitivity analysis of the base case models was conducted to investigate the potential of saving energy. In this type of sensitive analysis, the design and operation of the models are different in investigating the decision to adopt the other model's elements and parameters to the base case. Each model has different base case specifications, which were investigated by elements with the actual home in Dammam city, incompatible with the code, and the net-zero "Restar4" model (see Table 6.1). Moreover, each parameter and element compared the three models' construction specifications during the sensitivity analysis to investigate the base case potential to enhance the construction specifications and save energy.

Table 6.1 Model specification comparison of the Net Zero Restar4 model, base case, and Actual home.

` Parameter	Restart4 (Casini,2018)	The Base Case Model	Dammam City's Actual Home
Location	Dubai, UAE	Dammam city, KSA	Dammam city, KSA
External Wall U-Value (W /M ²K)	25 mm cement board, vapour barrier,50mm aerogel blanket,124mm Five-layer Dolomiti panel, 50mm tech interspace, 10 mm aerogel blanket (0.182 W /m ²K)	25mm stucco+250mm sandwich concrete block EPS filled core +25mm stucco (0.41W /m ²K)	25mm stucco+100mm concrete block+25mm EPS+100mm concrete block+25mm stucco (0.7 W /m ²K)
Double-Glazed Window System U-Value (W/M²K)	SGG Planitherm One Inox (U-value= 1.0 w /m ²k , SHGC= 0.45)	Openable double-glass windows (6mm/ gap/6mm) (1.25 W /m ²K)	The selected designs are evaluated under high-performance double glazing (U-value= 1.317 W /m ²K
Window-To-Wall Ratio (wwr)	21% of the gross wall area (32 m²),	8 % of the gross wall area (31 m²),	7% of the gross wall area
Roof U-Value (W /M ²K)	12.5 mm cement board, 80 mm aerogel blanket, 12.5 mm cement board, 124 mm Five-layer Dolomiti panel, 300 mm Tech interspace (0.131 W /m ²K)	25mm terrazzo tiles+25mm mortar+ 4mm bitumen layer+ EPS 50 mm +150 mm cast concrete +25mm stucco (0.43 W /m ²K).	25mm terrazzo tiles+25mm mortar+ 4mm bitumen layer+150mm castconcret +25mm stucco+25mm gypsum board (0.7 W /m ²K)
HVAC System	Fan coil Unit EER of 3.62 & COP 3.91	Mini-Split Unit EER 2.5 & SEER 3.6	Residential System (Constant-Volume DX AC), EER 2.3& SEER 3.2
Infiltration Rate (ACH)	0.2 ACH	0.25 ACH	0.35 ACH (assumed)
Simulation Set-Point (Heating And Cooling)	24ºC for Cooling, 17ºC for Heating	23ºC-24ºC for Cooling, 21ºC-18ºC for Heating	22ºC-24ºC for Cooling, 22ºC-19ºC for Heating
Equipment & Lighting Power Density	Per (w) Fridge 1.5, Washing machine 1820 ,Dryer 950 ,Dishwasher 2200 ,Oven 3650, Hob 3700 ,car recharge 3704, Pumps 250, TV 154, PC 120, Lights 588, 4 Demotic devices 433.	Lighting: 1.6 W/ m², Refrigerating: 1.8W/ m², cooking: 12W/m², misc.: 4W/ m² People: 90W/ person.	5 W/ m² guest zone, 7 W/ m² living & sleeping zones, and 30 W/ m² kitchen zone (Depending on space)
Energy Use Intensity (Kwh/M²/Year)	47.4 (kWh/m² /year)	126 (kWh/m² /year)	146 (kWh/m² /year)

The sensitive analysis targets the primary building systems parameters, including walls and roof U-values, HVAC-COP, AC/set-point, infiltration, and windows SHGC. Moreover, from the base case as a reference, each building's parameters were changed at ones according to the actual home and the net-zero home specifications. The reason for this analysis is to investigate the potential of saving energy in each building's parameter.

The investigation indicates that the most potential for saving energy was increasing the efficiency of the HVAC system. By applying the HVAC efficiency specification of the Net-Zero home on the base case, the EUI decreases by 25%. On the other hand, applying the actual home's HVAC efficiency increases the base case EUI by 7%. Moreover, the second important parameter was the wall's U-values; increasing the base case walls' U-values to meet the Net-Zero Home specifications decreases the base case EUI by 3.9 %. Figure 6.6 shows a base case sensitivity analysis of other specifications.

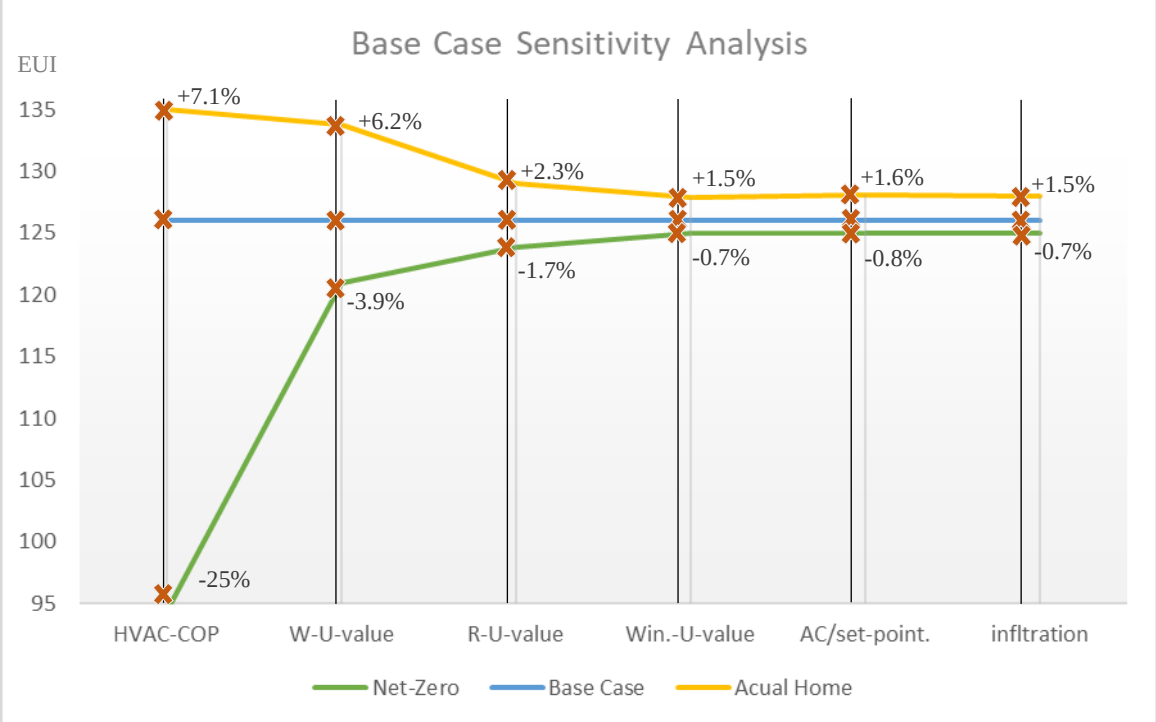


Figure 6. 6 base case sensitivity analysis in reference to the specification of the actual home in Dammam city and the net-zero "Restar4" model.

6.2.2- NZEH Decision-Making Development

As the literature review indicated in Chapter Three, most NZEH cases have reached the zero-energy level through active and passive measures. Usually, the design stage begins by enhancing the building envelope quality and then applying energy efficiency measures. As the base case sensitive analysis suggests, a profound focus on the HVAC system efficiency and the building envelope features is essential to target the most building energy consumption factors. Moreover, in most cases, when the building reaches a low energy consumption level of below 70 kWh/m2 /year, renewable energy is used to cover what is left of the energy consumption to achieve the Net-Zero energy stage.

Consequently, the design will begin in this decision-making process by enhancing the quality of building construction specifications. Then, a set of energy-efficient measures and sustainable design features will be Proposed to reach the low electricity consumption level. After that, the applicable renewable energy technologies will be explored to cover the base case's low energy consumption levels. Ultimately, the most compatible combination between the measures and renewable energy will be selected based on (cost and efficiency) to reach the Net-Zero stage.

6.2.2.1-Enhancing Building Construction Specification Quality

The base case primary construction specifications will be enhanced by 50 % and 100%. The main reason for this experiment is to investigate the influence of increasing the quality of building construction specifications on saving building energy consumption in terms of cost and efficiency (see Figure 6.7). As the case-sensitive base analysis suggests, the emphasis will be on most building factors that increase total building energy consumption, including HVAC efficiency levels and heat gain from external walls, roofs, and windows.



Figure 6. 7 base case section showing the building envelope components that will be enhanced and tested.

Table 6.2 shows the base case primary construction specifications with an enhanced efficiency of 50 % and 100% to estimate the potential of saving energy from increasing the construction specification quality.

Table 6.2 base case primary construction specifications with an enhanced efficiency of 50 % & 100%.

Parameter	Base case	+50% efficiency	+100% efficiency
External Wall U-Value (W /M ²K)	25mm stucco+250mm sandwich concrete block 50 mm EPS filled core +25mm stucco (0.41W /m ²K) (30cm)	25mm stucco,150mm L.W concrete block, EPS. 50mm, 150mm L.W concrete block,25mm stucco (0.25W /m ²K) (40cm)	25mm stucco,150 mm L.W concrete block, EPS. 100mm, 150mm L.W concrete block,25mm stucco (0.13W /m ²K) (45cm)
Double-Glazed Window System U-Value (W/M²K) (only glass)	Openable double-glass windows (6mm/ gap/6mm) (1.25 W /m ²K)	Openable triple Low-E glass windows filled with Argon. (6mm/ gap/6mm/gap/6mm) (0.82 W /m ²K)	Openable triple Low-E glass windows filled with coR. (6mm/ gap/6mm/gap/6mm) (0.47 W /m ²K)
Roof U-Value (W /M ²K)	12.5 mm terrazzo tiles+12.5 mm mortar+ 4mm bitumen layer+ EPS 50 mm +150 mm cast concrete +25 mm stucco (0.43 W /m ²K). (25 cm)	12.5 mm terrazzo tiles+12.5 mm mortar+ 4mm bitumen layer+ EPS 100 mm +150 mm cast L.W concrete +25mm stucco (0.21 W /m ²K). (30 cm)	12.5 mm terrazzo tiles+12.5 mm mortar+ 4mm bitumen layer+ EPS 100 mm +200 Aerated Concrete Slab+25mm stucco (0.18 W /m ²K). (35 cm)
HVAC System	Mini-Split Unit EER 2.5 & SEER 3.6	Mini-Split Unit EER 3.75 & SEER 5.4	Mini-Split Unit EER 5 & SEER 7.2

The analysis showed that increasing the base case's construction specification efficiency by 50% helped decrease the EUI by 21.5 %. Moreover, when the Base case construction specification efficiency is doubled, the EUI reduces by 30.2 %. Abruptly, the analysis showed that increasing the base case construction specification efficiency from 50% to 100% reduced the EUI by just 9%, which is considered a deficient percentage compared to the initial cost of increasing the building efficiency (see Figure 6.8).

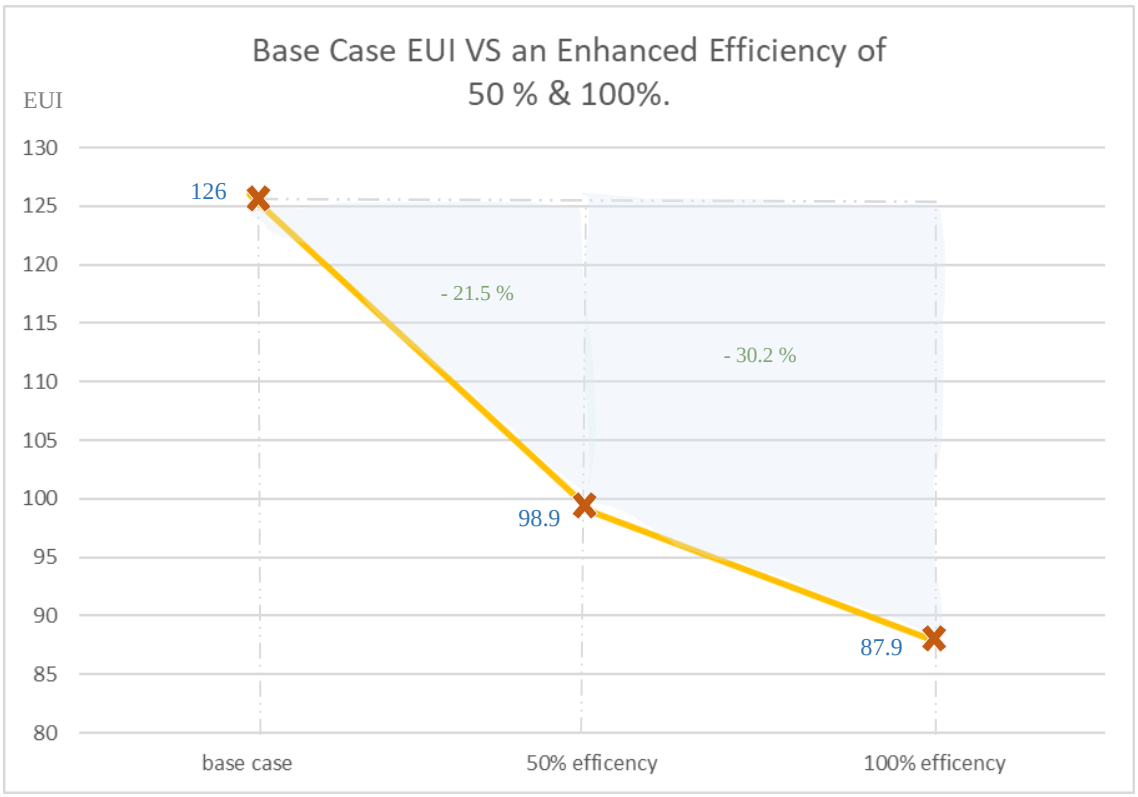


Figure 6.8 Base Case EUI VS an Enhanced base case Efficiency of 50 % & 100% With the reduction percentage in each Enhancement.

9.2.2.2-Applying Energy Efferent Measures & Sustainable Design Features

In this step, the base case energy consumption efficiency will be enhanced by applying some efficient and sustainable measures, which will be selected depending on the analysis of the Dammam city survey and the previous literature review in this research. Each measure will be applied individually to measure the actual. Effect of each enhancement. On the other hand, some of the selected measures might be eliminated in the final design depending on the relation between the cost and energy-saving efficiency of each tested measure. The measures that have been selected include window shading, building shape and orientation, natural ventilation, daylighting, HVAC system efficiency and thermostat setback point.

- Window Shading

The base case openings will be redesigned by applying shading devices. The shading device's effect on the building's opinions will be investigated. This includes the building envelope solar heat gain, cooling sensible load, people satisfaction and the total building electricity consumption. Using the sun cast future in the IES-VE simulation, many alternative designs have been applied to ensure that the window will be shaded without upsizing or oversizing for the shading device (see Figure 6.9).



Figure 6.9 Base Case SketchUp model on the left and the IES base case model with window shading enhancement to the right. This is the first alternative in using the shading device, which has been develop later in the design.

The window shading design has been changed to many alternatives to ensure that the window is covered for the whole year and to allow as many views as possible and lighting percentage to penetrate the home, which increases the daylighting and space's lux. Figures 6.10 and 6.11 show the final shading device design and dimensions according to the sun cast feature, which ensures window coverage in all seasons by using a sun path method.

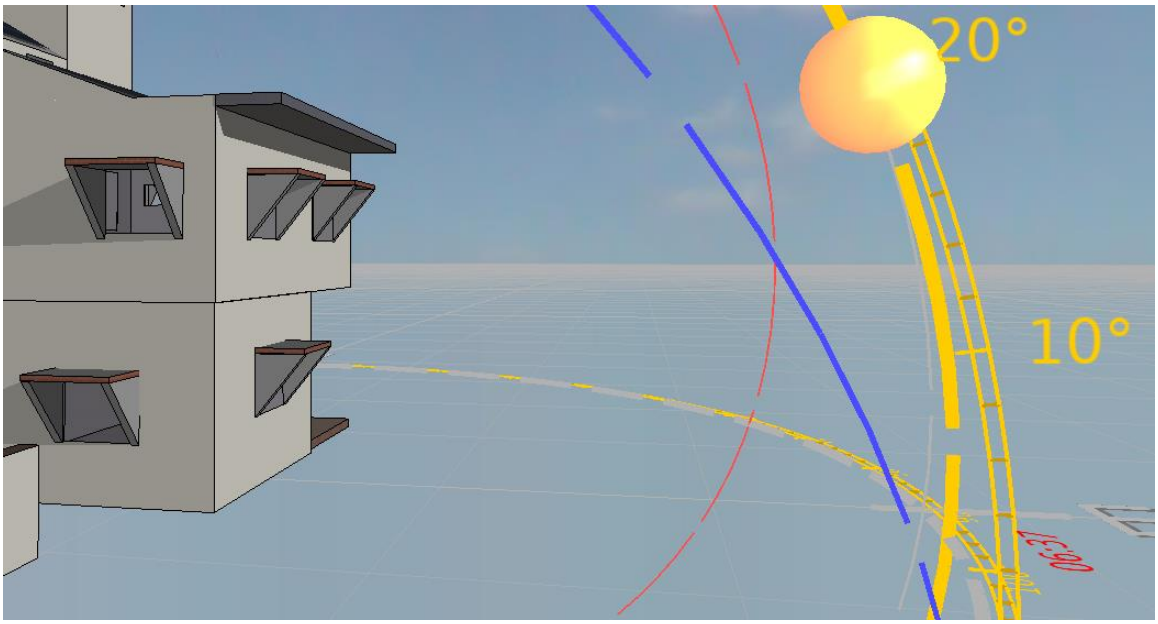


Figure 6.10 uses the sun cast feature in IES to determine which is the best shading device that ensures the whole window's coverage without under sizing the design and selection.

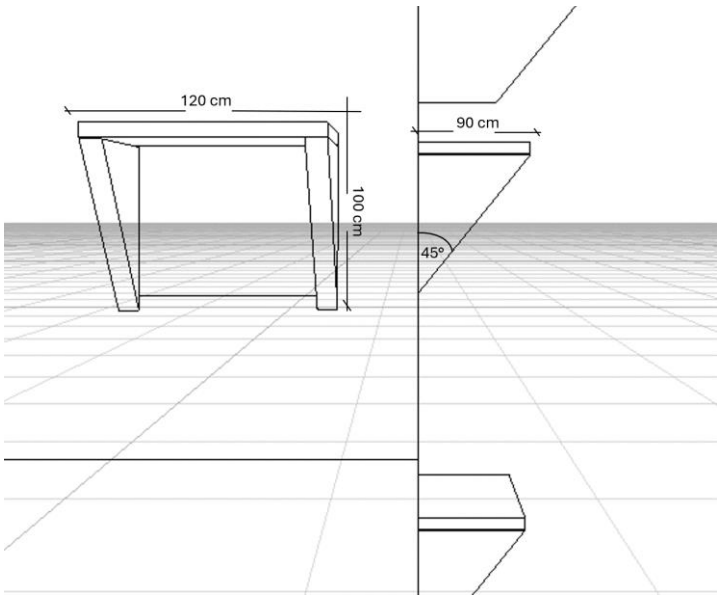


Figure 6.11 uses the sun cast feature in IES to determine the suitable window shading device dimensions that is cover the window area from sun in the whole year.

The shading devices helped reduce the solar peak heat gain by 70 %. On Aug.15, The peak solar heat gain decreased from 2.7 kW to 0.9 kW after applying the shading device (see figure 9.12). Moreover, the sensible cooling load has been reduced by 8.5% after using the shading devices. In fact, the peak sensible cooling load was reduced from 25 kW to 23.5 kW (see figure 6.13). Regarding thermal comfort, people's satisfaction increased by 7.2% (see figure 6.14). In the end, in general, the Building's total energy consumption was reduced by 3.4 %.

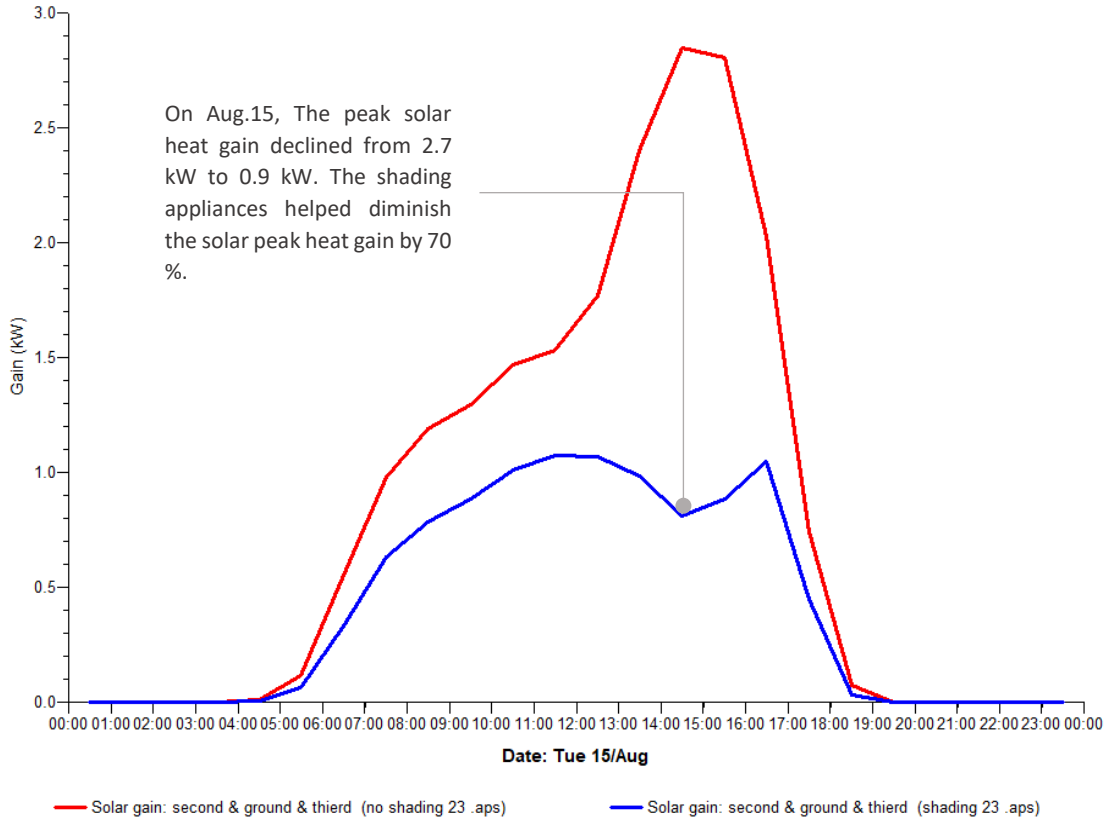


Figure 6.12 IES Base Case solar heat gain on Aug.15 before and after using the windows shading device.

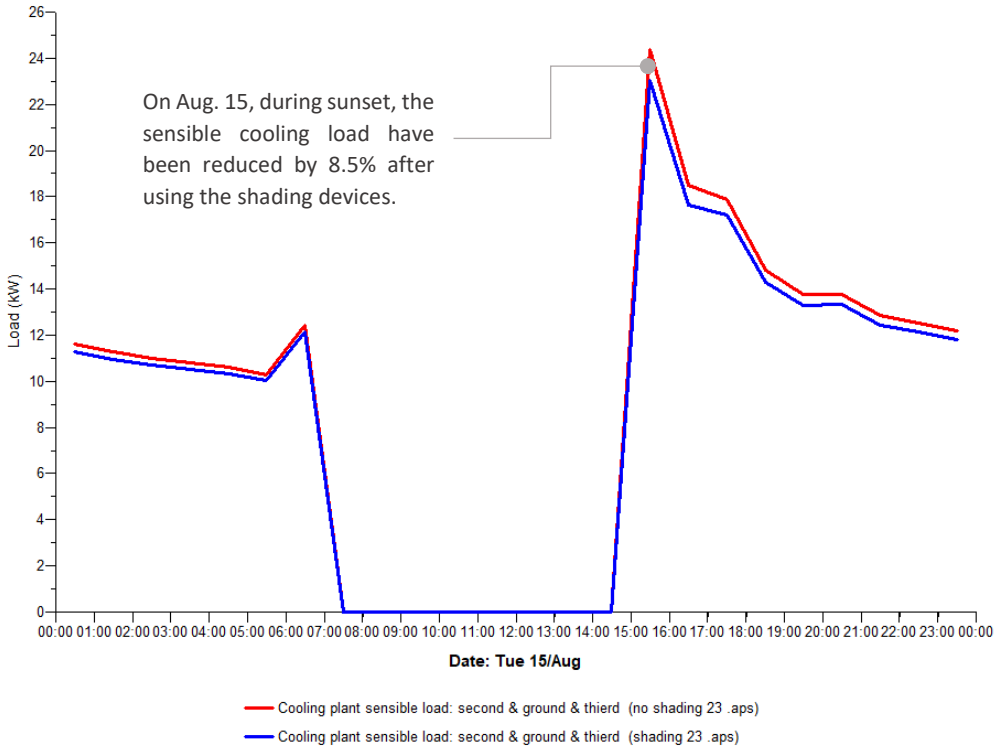


Figure 6.13 IES Base Case's cooling sensible load on Aug.15 before and after using the windows shading device.

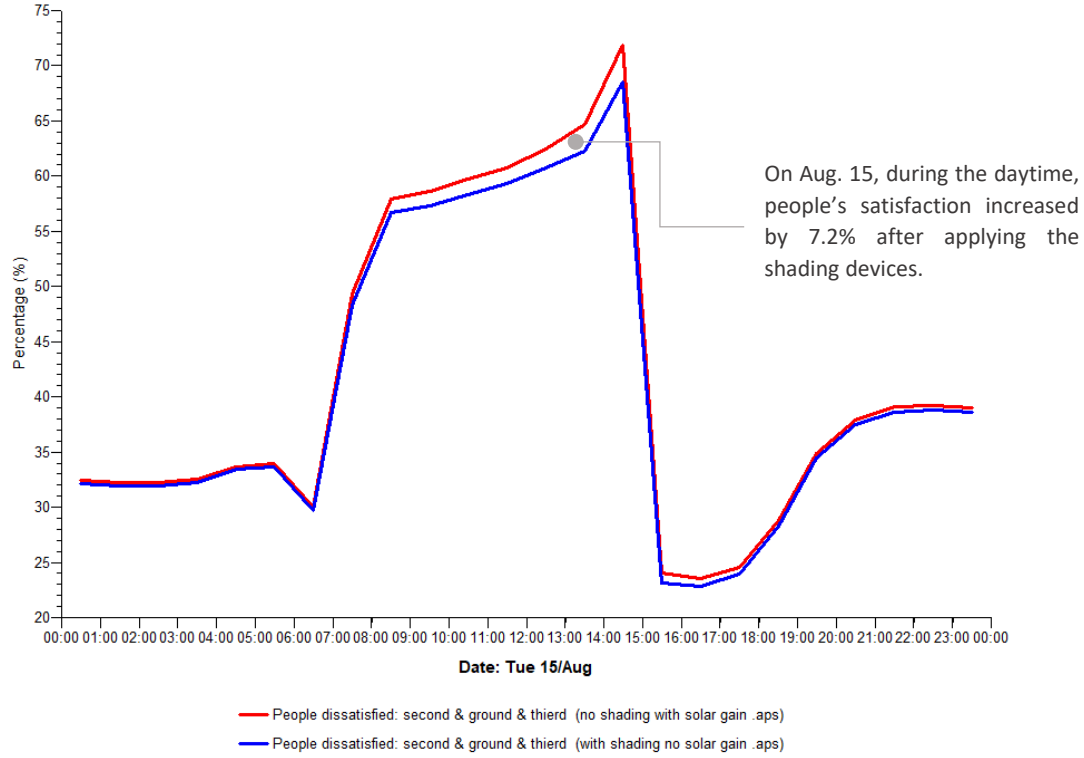


Figure 6.14 IES Base Case people's dissatisfaction on Aug.15 before and after using the windows shading device.

- Natural Ventilation

In this step, natural ventilation will be introduced to the home through a wind catcher, wind scopes and an operable door. The base case main geometry design has been developed to re-engage the natural ventilation strategies in the home. The natural ventilation strategies will work only if the room temperature is higher or equal to the outside air temperature (room temp. ≥ outside air temp.). The idea behind the design is to utilise the staircase area to make it work as a wind catcher. It simultaneously serves as a central area to distribute the air throughout the home spaces allowing hot air to escape the building (see Figure 6.15).

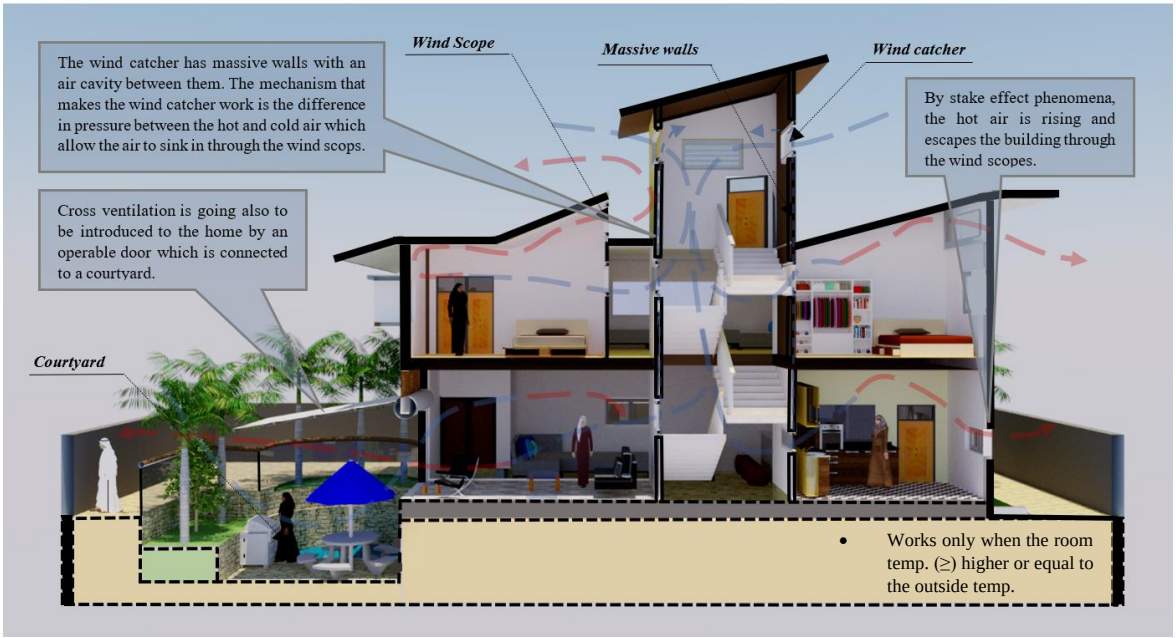


Figure 6.15 the Base Case has been redesigned by applying a wind catcher, an operable door and wind scopes to introduce cross ventilation to the building .

The natural ventilation geometry has been developed and analysed using the Microflow feature in the IES energy simulation program. The Microflow feature calculates the average airflow the building can receive throughout the year. The airflow volume that the building gets determines the total heat loss throughout the ventilation process, which then the energy

conservation can be estimated. As (Hawker, 2008) describes, the wind tower has two ends and a shaft. One rises via the roof as the upper part with a maximum of four openings, and the other reaches the end of the cellar, which could “discharge opening.” The base case wind catcher has been designed considering (Sanij, 2015) recommendations with diminution of 2.6 x 2.6 x 3.6 m. Moreover, on each floor, a discharger opens to allow air distribution throughout the whole building space (see figures 6. 16-17).

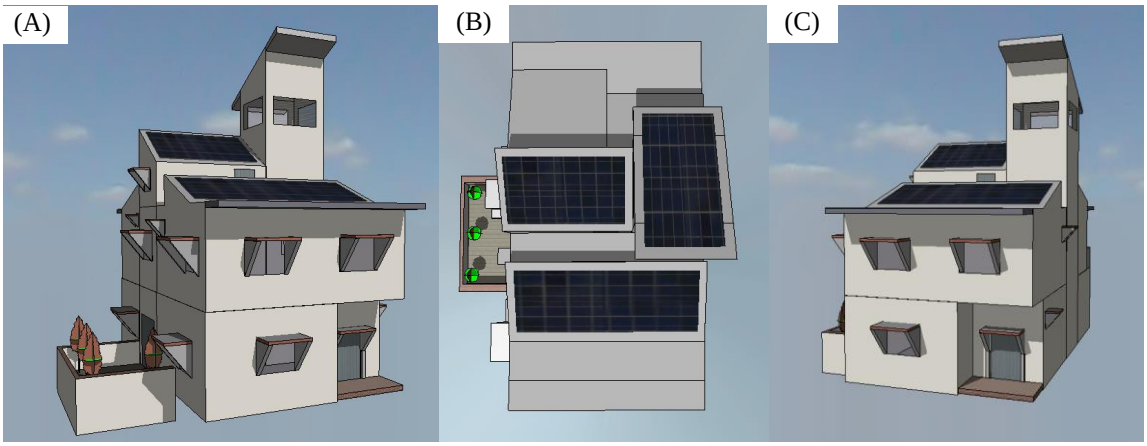


Figure 6.16, the base case geometry on the IES energy simulation program, shows the natural ventilation measures introduced to the base case .

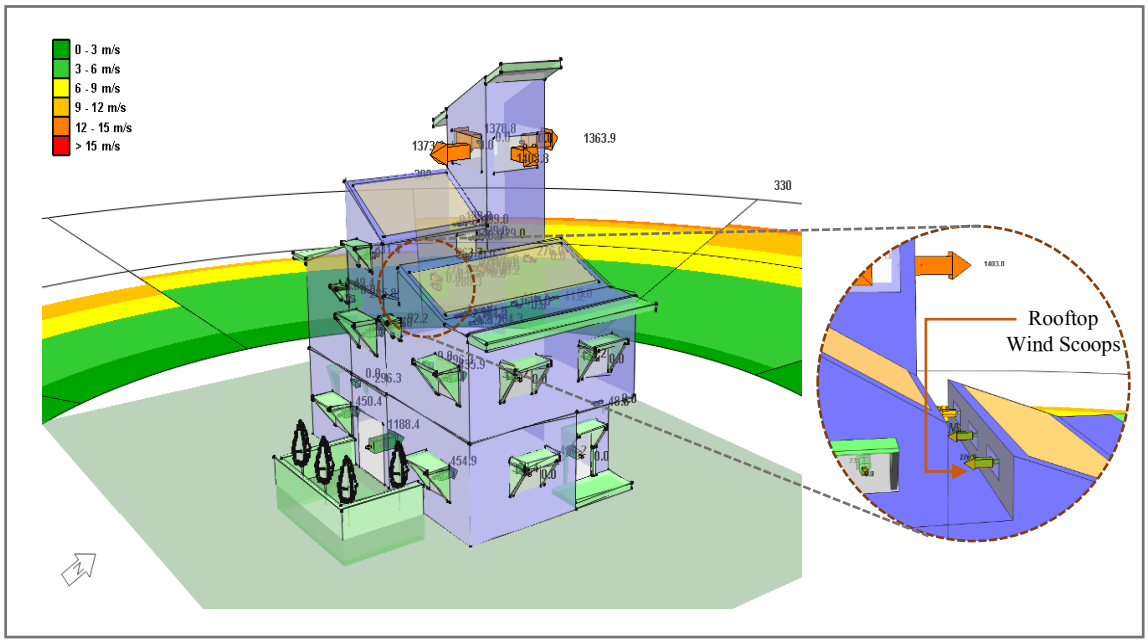


Figure 6.17 IES Microflow analysis feature shows the base case natural airflow movement through the home openings.

Figures 6.18 and 6.19 show the “fx” function feature in creating the Windcatcher annual operating profiles. The Windcatcher operational input equation is selected when the outside air temperature °C is less than or equal to the room air temperature °C, and the Windcatcher will operate. Assuming that the windcatcher louvers' openings operate with actuator sensors that follow the selected operation function equation.

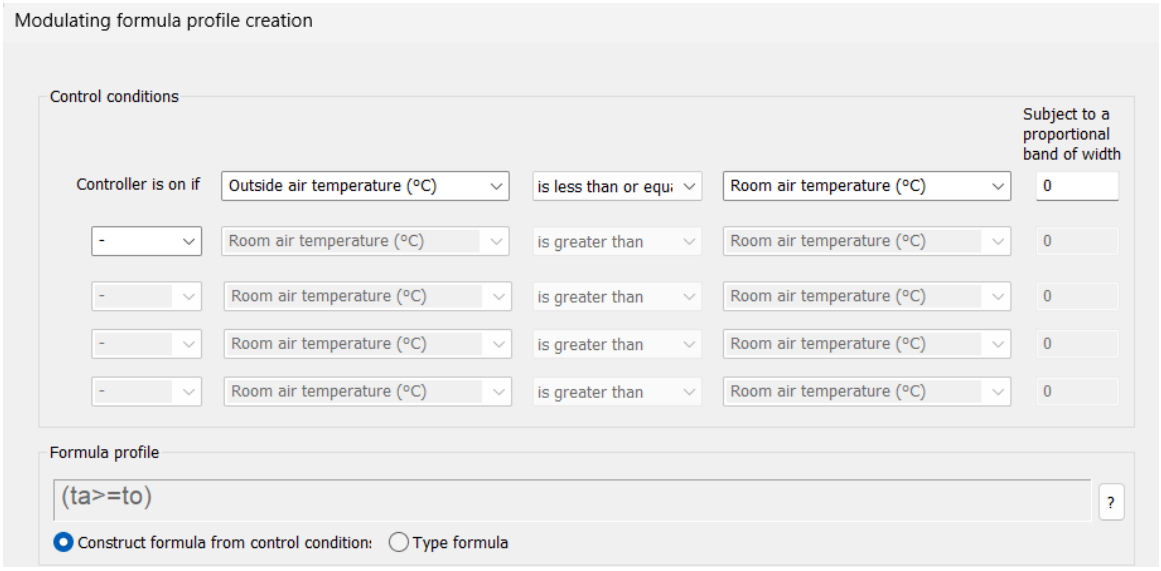


Figure 6.18 IES formula function profile creation for Windcatcher thermal operating profiles.

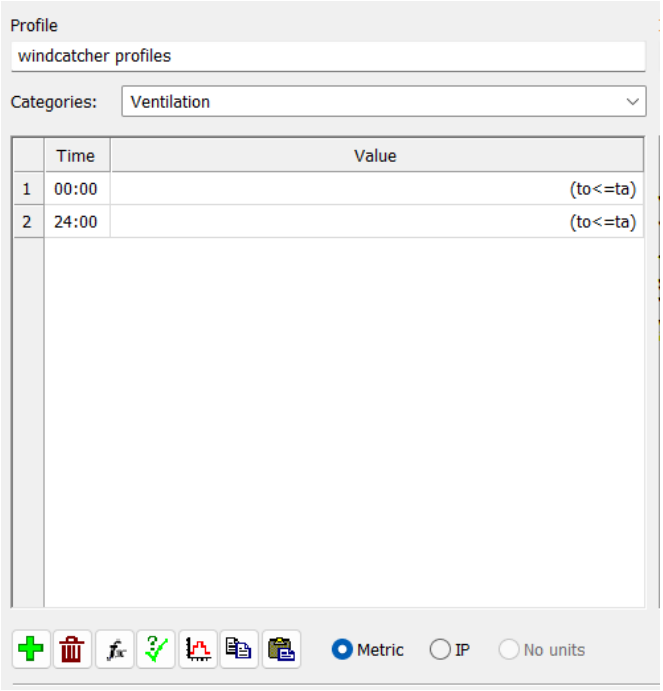


Figure 6.19 IES Daly profile feature as the first step for creating Windcatcher annual operating profile. Showing the windcatcher operating formula (to<=ta)

After performing the simulation through the microflow feature, the result showed that, in the summer, the home would not receive any natural ventilation for the months of (Jun, Jul, Aug, and Sep) since the natural ventilation will stop if the external temperature is more elevated than the room temperature. On the other hand, in certain winter months, the total natural ventilation the building can receive exceeds 20000 l/s. Furthermore, the average natural ventilation throughout the year (volume flow) the house receives from all geometry inlets is around 4239 l/s. (see Figure 6. 20-21).

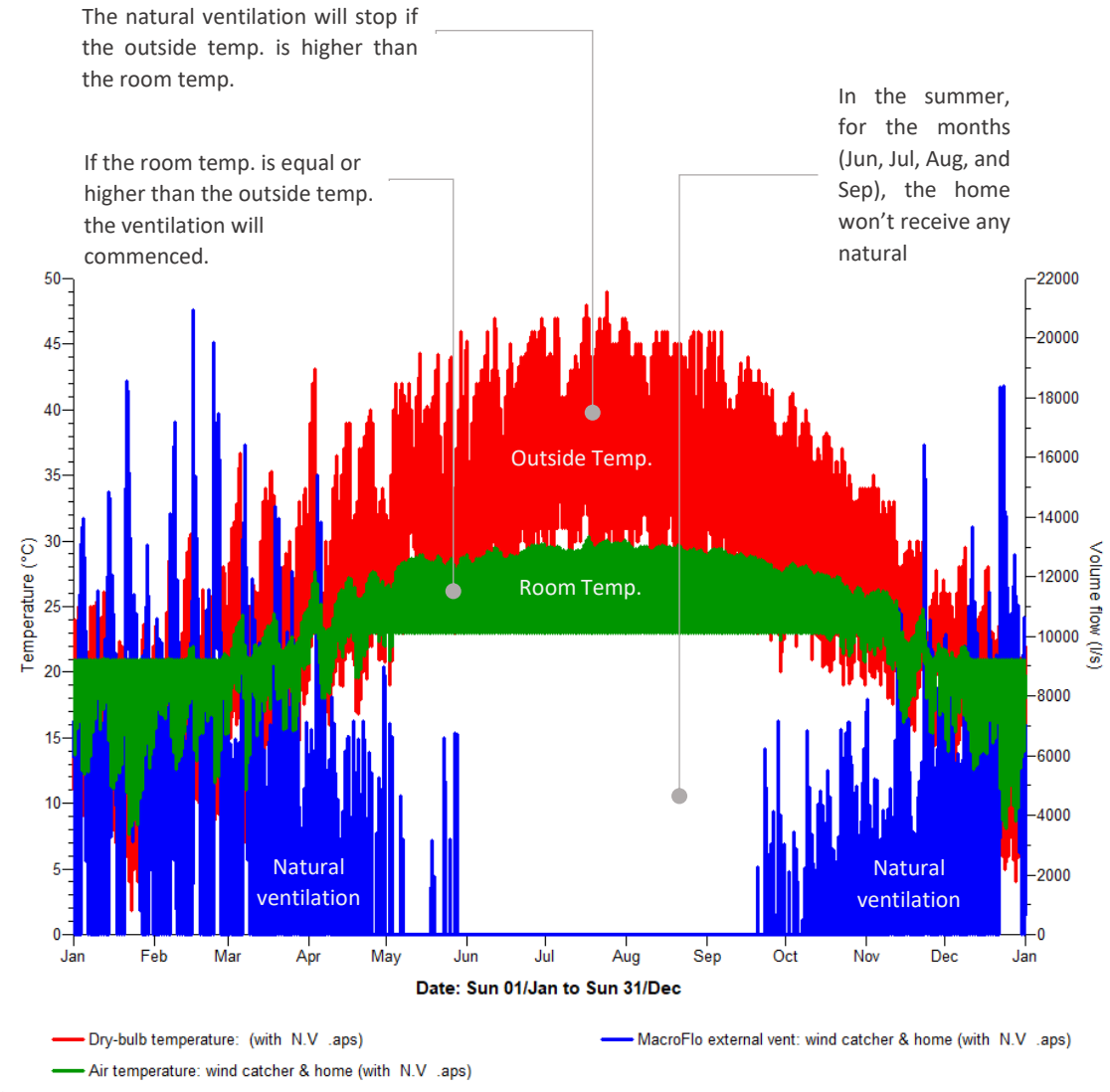


Figure 6.20 shows the relationship between base case outside temperature, room temperature and natural ventilation.

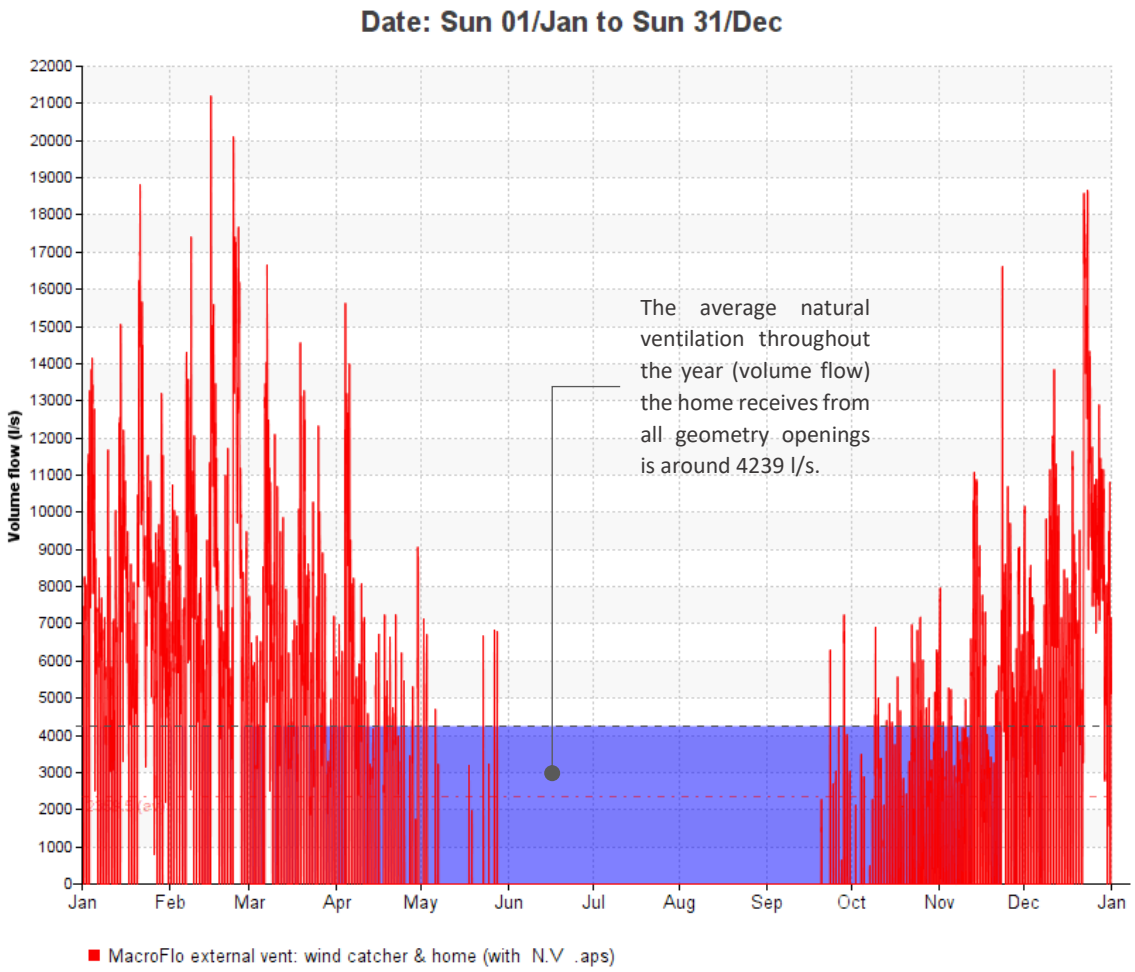


Figure 6.21 shows the average natural ventilation throughout the year (volume flow) that the home receives from all geometry openings.

On the other hand, regarding building CO2 concentrations, During the day, the outside temperature is more elevated than the inside, preventing natural ventilation. Hence, the high CO2 concentrations are connected directly to the absence of ventilation during noon. In fact, during noon, the CO2 consecration exceeds 1000 ppm, which, According to (OH&S, 2016), will be associated with complaints of drowsiness and poor air. Likewise, natural ventilation helped reduce home carbon emissions (kgCO2/h) by 9.8% (see Figure 6. 22-23).

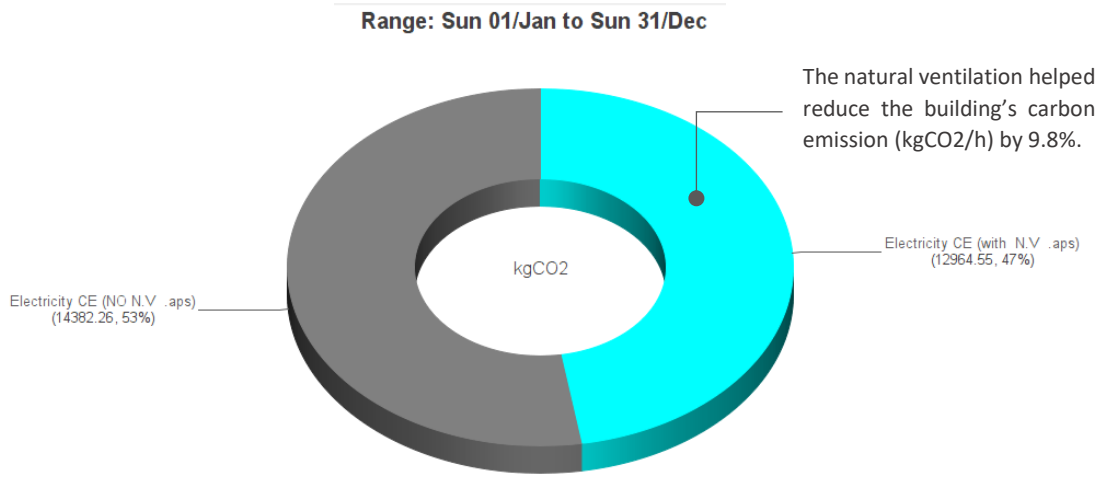


Figure 6.22 compares the building's CO2 emission (kgCO2/h) before and after using natural ventilation.

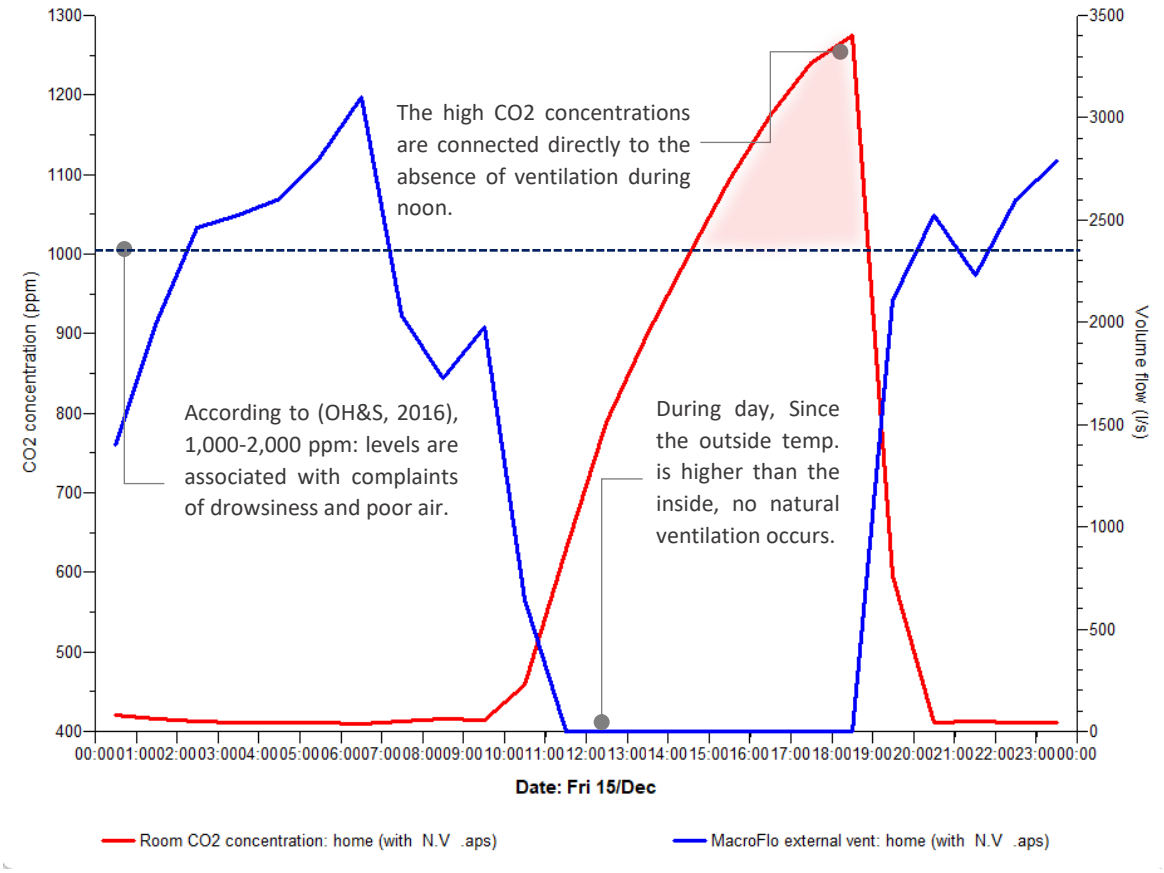


Figure 6.23 shows the relation between CO2 concentration and introducing natural ventilation in the base case on the 15th of December.

Regarding home energy consumption in general, natural ventilation helped reduce the building's space cooling consumption (MWh) by 17% and its total electricity consumption (MWh) by approximately 10% (see Figure 6. 24-25).

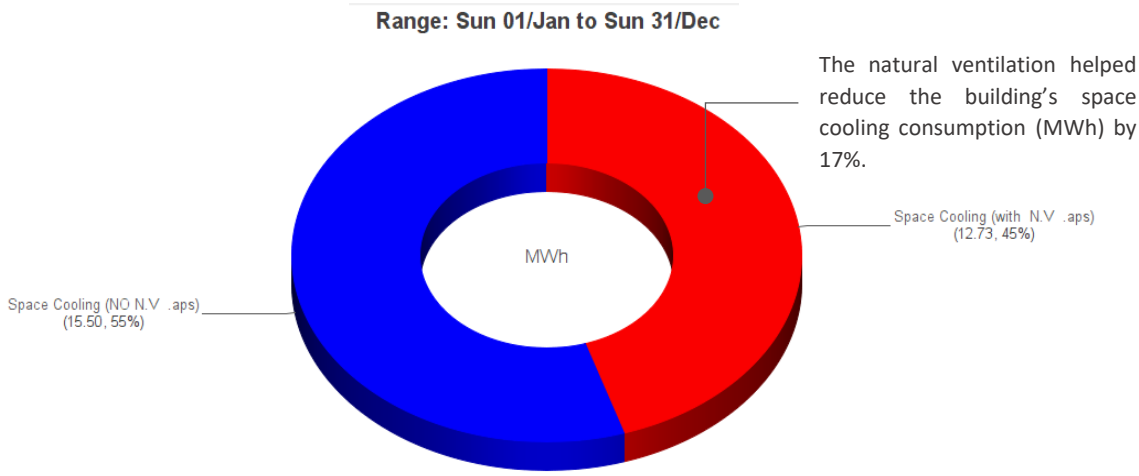


Figure 6.24 compares the building's space cooling before and after using natural ventilation.

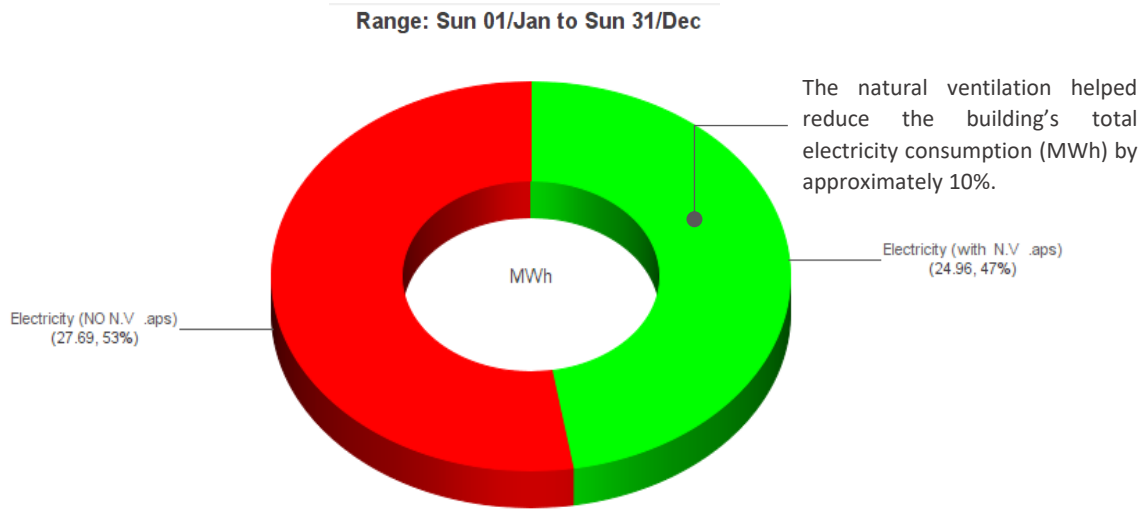
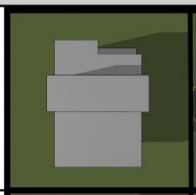
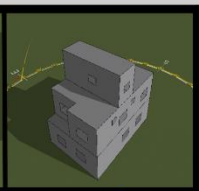
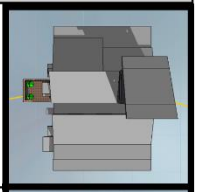
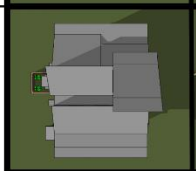
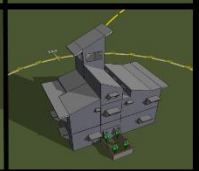
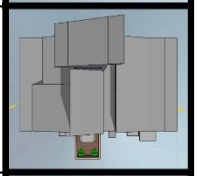
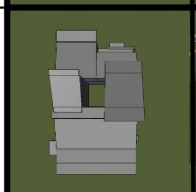
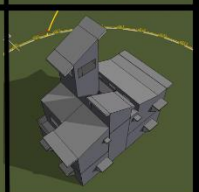
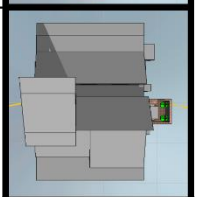
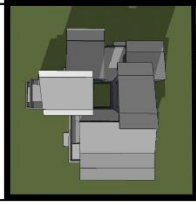
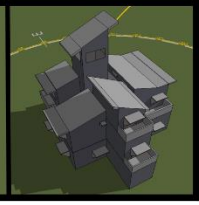
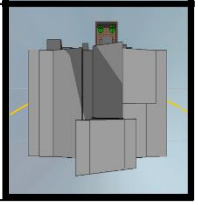


Figure 6.25 compares the building's total electricity consumption before and after using natural ventilation.

- Building Shape and Orientation

Decisions about basic building geometry design and the importance of minimising heat gain in the summer and heat loss in the winter are made at the initial stage of architectural drawings. Simultaneously, deciding the optimum building orientation is usually done in the early design phase. The base case has been redesigned in various shapes and orientations to measure the effect of minimising heat gain on the building envelope. The base case's original geometry was redesigned in three different scenarios, including adding an external courtyard, redesigning the building envelope to shade itself and investigating our ancestor's method of building their homes by including a central courtyard. Moreover, the effect of changing the base case orientation is measured by redirecting the basics to the four main elevations N, E, S and W (see Table 6.3).

Table 6.3 variety of base case geometry shapes & and orientations, including each shape remarks

Building shape				Building orientation	
1- Original Base Case			The base case geometry wasn't designed with a courtyard or window shading device because it was designed according to the survey. Also, natural ventilation wasn't introduced in this trial. The base case is designed without regard to the aerodynamics of air with an ordinary flat roof.	*1-North*	
2- Exterior Courtyard			The base case was enhanced at the natural ventilation stage by applying an external courtyard with windcatcher works only if room temp..≥ outside temp. Also. In this trial, the roof was designed to allow the circulation of air by creating wind scoops.	*2-East*	
3- central Courtyard			In this home geometry design, the courtyard was moved from the building's external envelope into the Centre of the building as our ancestor's way of designing their own homes. The decision behind this design is to investigate how moving the courtyard to the center of the building will affect the total EUI.	*3-South*	
4- self-shading shape			In this experiment, the home is designed with respect to the geometry-self-shading strategies. In addition to the central courtyard, the home geometry was redesigned to cast a shade on the building envelope. The desiccation behind the design is to measure whether making the building shade itself decreases the total EUI.	*4-West*	

The effect of changing the base case orientation on the solar heat gain was a range of 4% disparity between all elevations. After the comparison, The North elevation considers the feasible exposure between all elevations, with solar heat gain of around 5.8 MWh yearly. On the other hand, in investigating the effect of changing shape on solar heat gain, Constructing the home with a central courtyard helped decrease the Solar heat gain from 7.2 MWh in the base case to around 5.85 MWh yearly. Unexpectedly, the self-geometry shading strategy needed to be more feasible. The solar heat gain increased by 5.6 % after adding the self-shading geometry because the home horizontal surface area equals or less than the self-shading geometry. At the end of this investigation, the most feasible option is to redirect the base case toward the north and redesign the courtyard to be at the center of the home (see Figure 6.26).

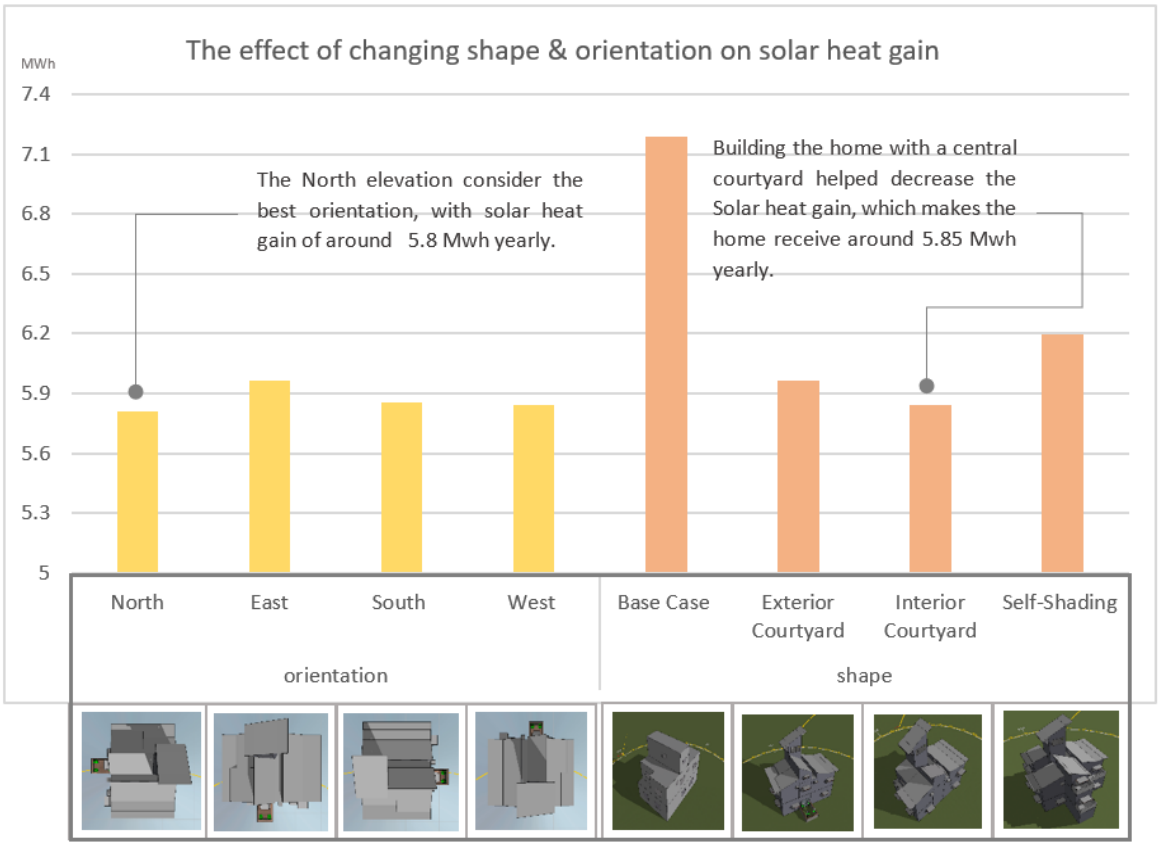


Figure 6.26 the effect of changing the base case shape & orientation on solar heat gain).

- Daylighting

The previous chapter designed the base case with an LED lighting system. Two main steps were included in the base case to get the most daylighting benefits. First, the IES-Flucs-DL feature rearranged the Base Case window distribution to get an average of 150-200 lux in most home areas (see Figure 6.27). Second, occupant-dimming profiles were added to the base case to minimize artificial daylight during the day. After the simulation, the result showed a minor total energy consumption reduction of 1.6%. This was a neglected reduction percentage because the base case had already been designed with an energy-efficient LED lighting system before the enhancement procedure.

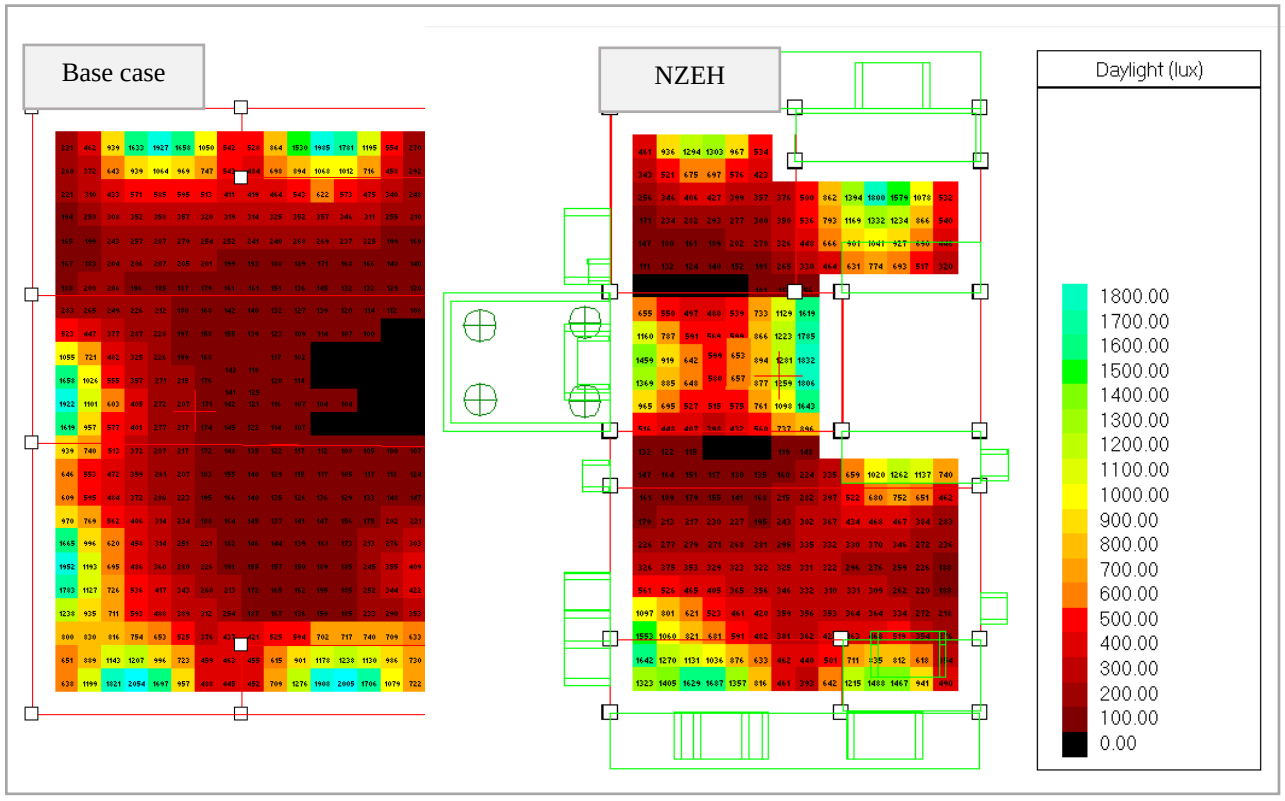


Figure 6.27 IES graph showing enhancement for Base Case daylighting distribution through the Flucs-DL feature, which compares the base case on the left to the NZEH on the right.

See Appendix F for more information about the IES's daylighting input, including the building template manager that shows the daily lighting dimming profiles.

- HVAC Efficiency & Thermostat Setback point

The most efficient option was to enhance the HVAC system's base case efficiency by 50%. The initial baseline SEER has risen from 3.6 to 5.4, indicating a significant decrease in energy use of 24%. Conversely, adjusting the cooling set-point upwards is a simple and cost-free method that does not compromise the comfort of occupants. In the initial configuration of the base case, the cooling system is programmed to operate based on the occupancy profile. This means that during the space-occupied hours, the set point temperature is maintained at 24°C throughout the year. The analysis revealed that by setting the thermostat to cool at a temperature range of 24°C-25°C, the system's energy consumption could be reduced by an additional 4.8%.

6.2.3- NZEH Prototype Final Design

The previous investigation enhanced the base case by employing sustainable design features and increasing the base model's energy efficiency consumption through EEMs. Some of those enhancements significantly reduced consumption; for instance, improving the home envelope U-vale by 50% has decreased energy consumption by 8%. Likewise, increasing the HVAC efficiency by 50% has reduced energy consumption by 24% (see Table 6.4).

On the other hand, some of the measures applied to the base case haven't shown any significant improvement in decreasing energy consumption. For example, reorienting the base case direction toward the north side has reduced energy consumption by 0.6%. Similarly, increasing daylighting by decreasing the reliance on artificial lights decreases energy consumption by 1.6% (see Figure 6.28).

Regarding passive cooling techniques, which include wind catcher, courtyard and wind scop, the result showed a reasonable reduction in the total energy by 10%. On the other hand, another thing to consider when selecting measures is the additional initial cost added to the base case and the estimated payback period of each measure, which will be investigated later in this research.

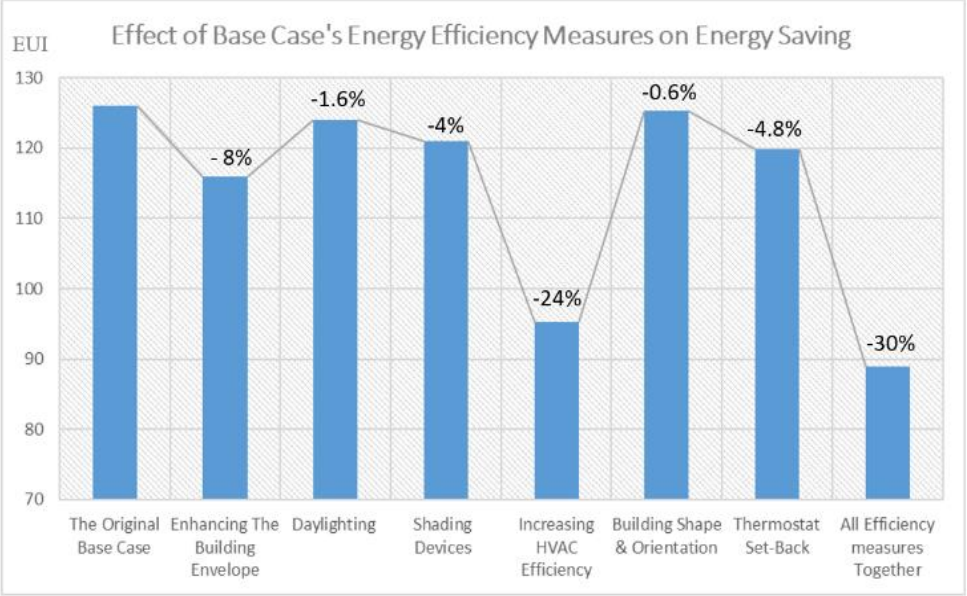


Figure 6.28 shows the Effect of the Base Case's Energy Efficiency Measures & passive cooling techniques on Energy Saving.

Table 6.4 The improved base case construction specifications &EEMs that have been simulated in the IES tool.

External Wall U-Value (W/M²K)	Home Glazed Window System U-Value (W/M²K)	Window-To-Wall Ratio (wwr)	Roof U-Value (W/M²K)
25mm stucco,150mm L.W concrete block, EPS. 50mm, 150mm L.W concrete block,25mm stucco (0.25W /m ²K)	Openable triple Low-E glass windows filled with Argon. (6mm/gap/6mm/gap/6mm) (0.82 W /m ²K)	8 % of the gross wall area (31 m²)	12.5 mm terrazzo tiles+12.5 mm mortar+ 4mm bitumen layer+ EPS 100 mm +150 mm cast L.W concrete +25mm stucco (0.21 W /m ²K)
HVAC System	Infiltration Rate (ACH)	Simulation Set-Point (Heating & Cooling)	Equipment & Lighting Power Density
Mini-Split Unit EER 3.75 & SEER 5.4	0.25 ACH	24°C-25°C for Cooling, 18°C-21°C for Heating	Lighting: 1.6 W/m², Refrigerating: 1.8W/m², cooking: 12Wm², misc.: 4W/m² People: 90W/person

6.2.3.1- Applying solar panel system.

As the Dammam city survey showed in previous chapters, the micro wind turbine was the most bypassed measure since 65% of participants did not appreciate installing wind turbines on the top of their residential roofs. Moreover, wind turbines have major disadvantages, such as electricity production efficiency and operational noise. Consequently, this research will focus on solar panels that generate energy within the home footprint (on-site). The solar panel calculation is designed to cover the total home energy consumption, around 46000 w/h/day (see Figure 6.29). Overall, solar system losses, including power loss in solar panels, account for roughly 26% of the energy generated (Bruce, 2023). The selected type of PV system is monocrystalline with 23% nominal efficiency (see Table 6.5).

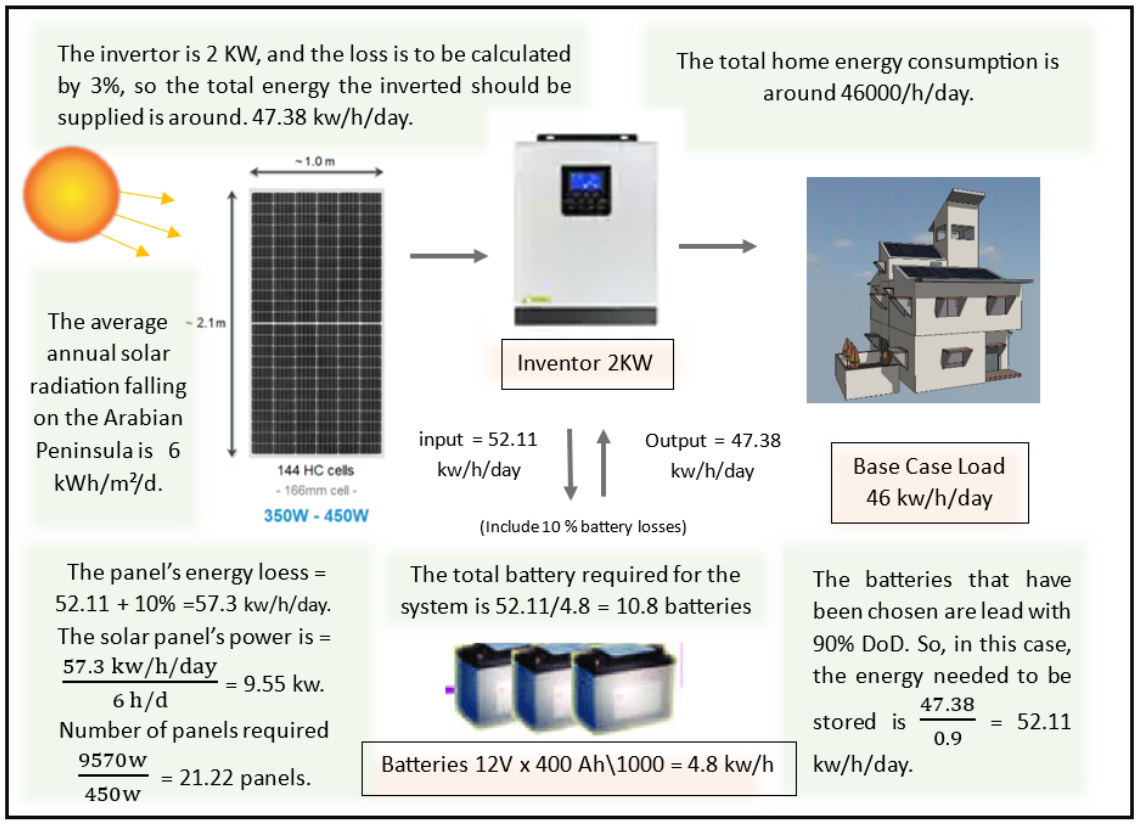


Figure 6.29 Base Case prototype's Solar system design includes batters and inventor requirements.

Table 6.5 Base case solar panel specification and type, which is linked to IES energy simulation tools.

Solar Panel Type	Module Nominal Efficiency	Nominal Cell Temp. (NOCT) (°C)	Reference Irradiance for NOCT (W/M²)	Temp. Coefficient for Module Efficiency Pmax (%/°C)	Degradation Factor	Electrical Conversion Efficiency
Monocrystalline Silicon	0.2300	42.0	1000	-0.3500	0.9900	0.9600

After satisfying the home's solar panel requirements, the total solar panel's power is calculated to be around 9.57 kW with a total number of panels required of 22 panels. The total solar panel area the home needs is around 46 m² which was simulated by the free-standing solar panels feature on the IES energy simulation program (see Figure 6.30)

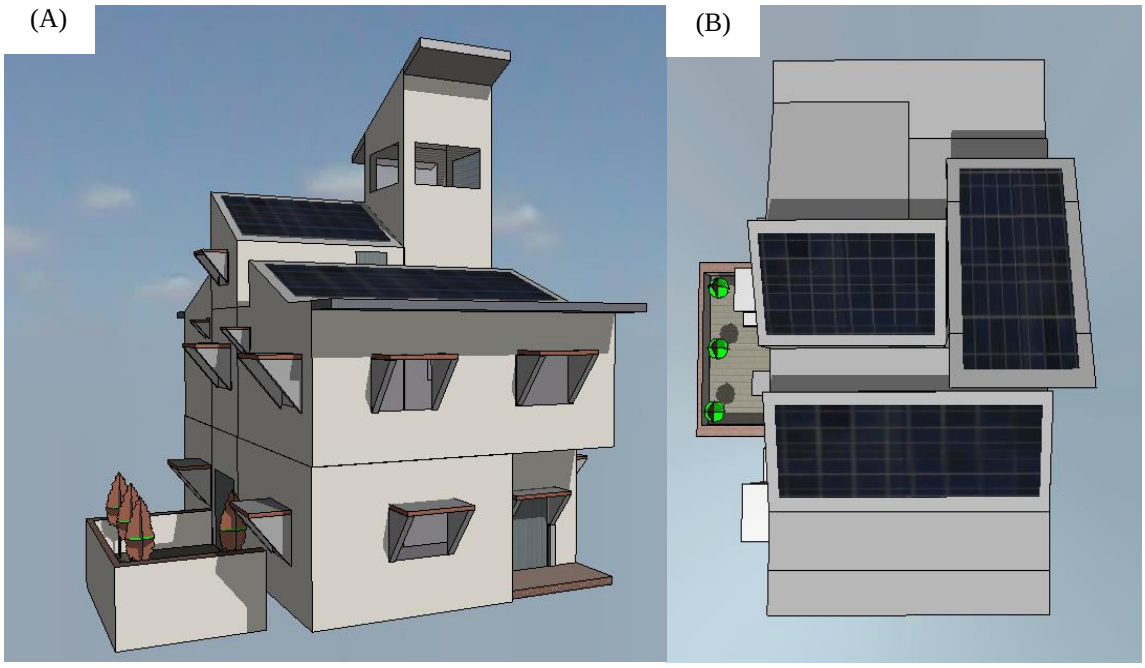


Figure 6.30 IES Base Case prototype's Solar panel system arrangements, by free-standing solar panels feature, containing 22 solar panels which cover 23 % of the roof area.

The IES simulation showed that the ZEH has become self-sufficient on an annual basis. The total electricity generated in the whole year from the PV system was 17.1 MWh, while the NZE-ready home consumption was around 16.6 MWh. Nevertheless, the solar panel system couldn't cover the total energy needed in the summer months from July to

December, with an average shortage of around 7%. Yet, as the calculation shows, the PV system has eleven batteries with a 4.8 kw/h capacity for each. Therefore, to avoid oversizing the solar panel requirement, it's better to do not increase the solar panel's power, especially since the shortage in the summer months is nominal (see Table 6.6).

Table 6.6 IES table showing a comparison between home electricity consumption & PV electricity generated.

Output Analysis Help

	Electricity (MWh)	PV generated electricity (MWh)
Date	solar panels run .aps	solar panels run .aps
Jan 01-31	1.0354	-1.0241
Feb 01-28	0.9352	-1.1490
Mar 01-31	1.0368	-1.4854
Apr 01-30	1.1693	-1.6041
May 01-31	1.6600	-1.8273
Jun 01-30	1.7868	-1.8031
Jul 01-31	1.9594	-1.7891
Aug 01-31	1.9210	-1.7101
Sep 01-30	1.6945	-1.5130
Oct 01-31	1.4016	-1.3312
Nov 01-30	1.0537	-0.9766
Dec 01-31	1.0354	-0.9495
Summed total	16.6891	-17.1625

6.4- NZE Prototype Added Cost Estimation.

The initial cost for a Net Zero Energy Home (NZEH) is generally higher than that of a conventional house. NZEHs are designed to produce as much energy as they consume over a year, usually through renewable energy sources. These energy-efficient technologies and design features cost more upfront than traditional building methods. Some factors contributing to the higher initial cost of NZEHs include Energy-efficient features. NZEHs incorporate advanced insulation, high-performance windows, efficient cooling systems, and energy-saving appliances. These technologies often have higher initial costs compared to their conventional peers. Moreover, the main cost-increasing factor is the solar panels or other renewable energy systems installed to generate the required energy. While the

long-term savings on energy bills offset the initial costs, the initial investment in these systems can be significant at the beginning of any home construction. In this investigation, cost estimation is only for the added cost to the initial base case. The NZEH estimation is divided into three main categories: the building envelope, the mechanical system, and the solar panel system. The cost estimation is for the Saudi Arabian market price by Saudi riyal. The quantity needed for each element is the added quantity the base case needs to function as a NZEH. Buying a villa in Dammam City costs around 5,000 RS/m² (Argaam, 2020). According to 2020 market prices, the total gross area in the base case scenario is about 220 m², so the base case market price will be around 1,100000 SR. On the other hand, as Table 6.7 shows, the NZE prototype added cost estimation for all building components, including materials quantity and labour work, is around 184,500 SR.

Table 6.7 NZE prototype added cost estimation for all building components, which was made specifically for this research case, including quantity and market price.

Category	Items	Market Price	*Quantity	*Cost Estimation (SR)	Source
Building Envelop	Bocks-20cm	1800 (SR/1000 U.)	950 U.	1,710	(ceicdata, 2023)
	Concrete -Resistant: 350 K	203 (SR/m³)	12.96 m³	2,630	(ceicdata, 2023)
	Iron: Local: 16 mm (epoxy)	3795 (SR/TON)	60 U.	4,296	(ceicdata, 2023)
	EPS-Bord-(125cm x 200cm x 4cm)	20 (SR/unit)	342 U.	6,840	(alrashed, 2023)
	Labour (excluding materials)	150 (SR/m)	24 m	3,600	(aqar, 2020)
	Windows triple glazed 1.2x1.2m	4150 (SR/unit)	14 U.	31,500	(theecoexperts, 2023)
	Finishing (including materials)	700 (SR/m)	12 m	8,400	(mqawla, 2020)
Mechanical System	HVAC	3200 (SR/ U.)	8 U.	** 5,600	(LG, 2023)
	Window Automatic Control	1400 (SR/ U.)	14	19,600	(e-hardware, 2023)
	Lighting Smart Home Control Panel	874 (SR/ U.)	9 U.	7,866	(Moes, 2023)
Solar Panels System	Including all System Components	8.43 (SR/w)	9570	80,675	(greenmatch, 2020)
	Batteries 12V – 400 Ah = 4.8 kw/h	1150 (SR/ U.)	10 U.	11500	(anern, 2023)
				*** ***Total Estimation = 184,500 SR***	

** The cost estimation is only for the added cost to the initial base case cost.*

** * The cost of the difference in price between the efficient and highly efficient for the whole home.*

** ** The cost of maintenance is excluded which costs around 1-4% of the total building value each year (statefarm,2024).*

Hence, the NZEH will cost 14.36 % more than the ordinary base case. The main reason for this increase is the solar panel system, which costs around 92,000 SR, 50% of the total prototype added cost. Another factor is the highly efficient triple window, which costs around 32000 SR for all the home openings.

6.5- NZE Prototype Greenhouse Gas Reduction Through Energy Savings.

The decrease in GHG emissions indicates the benefits of ZEHs to the environment and people's health. Since most of the electricity generation in region is driven by fossil fuel resources, including oil and natural gas, the electricity generation movement in this sector is responsible for releasing GHG emissions, including carbon dioxide (CO2). Table 6.8 below compares the base case and NZEH annual CO2 emissions. The CO2 emission was compared in whole building system categories, including lighting, equipment and other building systems. The CO2 emissions calculation method was done through the IES-VE energy simulation program, which covers the total building emissions in the whole year from 1 Jan to 31 DEC.

Table 6.8 Compares the yearly carbon dioxide (CO2) emissions of the Base case with a Net Zero Energy Home (NZEH). The carbon dioxide (CO2) emissions were compared across many categories of the whole building system, including lighting, equipment, and other building systems.

Base Case	Total CE (kgCO2)	Lights elec. CE (kgCO2)	System elec. CE (kgCO2)	Equip elec. CE (kgCO2)	NZEH	Total grid disp. elec. PV CE (kgCO2)	Lights elec. CE (kgCO2)	Equip elec. CE (kgCO2)	Total system CE (kgCO2)
Date	CO2 emission	CO2 emission	CO2 emission	CO2 emission	Date	solar panels run	solar panels run	solar panels run	solar panels run
Jan 01-31	729	46	297	373	Jan 01-31	-531	38	308	1701
Feb 01-28	661	41	283	337	Feb 01-28	-596	34	278	1063
Mar 01-31	957	46	539	373	Mar 01-31	-771	38	308	418
Apr 01-30	1297	44	892	361	Apr 01-30	-833	36	298	281
May 01-31	1727	46	1310	373	May 01-31	-948	38	308	517
Jun 01-30	1858	44	1454	361	Jun 01-30	-936	36	298	594
Jul 01-31	2082	46	1665	373	Jul 01-31	-929	38	308	672
Aug 01-31	2020	46	1603	373	Aug 01-31	-888	38	308	653
Sep 01-30	1749	44	1345	361	Sep 01-30	-785	36	298	546
Oct 01-31	1486	46	1068	373	Oct 01-31	-691	38	308	383
Nov 01-30	1038	44	633	361	Nov 01-30	-507	36	298	290
Dec 01-31	766	46	340	373	Dec 01-31	-493	38	308	1398
Summed total	16370	538	11431	4392	Summed total	-8907	444	3621	8515

Figure 6.31-32 shows that both the base case and NZEH CO2 emissions were analysed across many categories of the whole building system; the total base case CO2 emission is around 16370 kgCO2. Moreover, after applying the EEMs and passive cooling techniques to the base case, the NZEH emission decreased to 8907 kgCO2, which diminished the total base case CO2 emission by 46%.

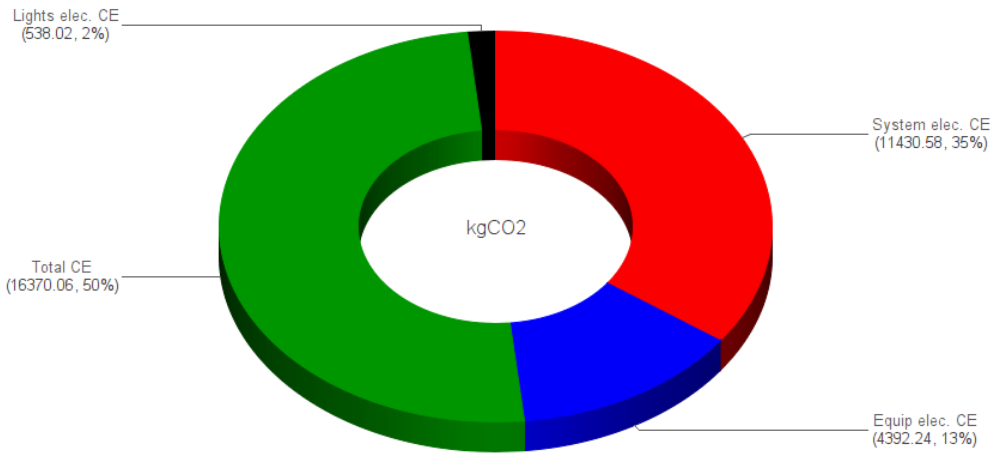


Figure 6.31 The Base case (CO2) emissions were analysed across many categories of the whole building system, including lighting, equipment, and other building systems.

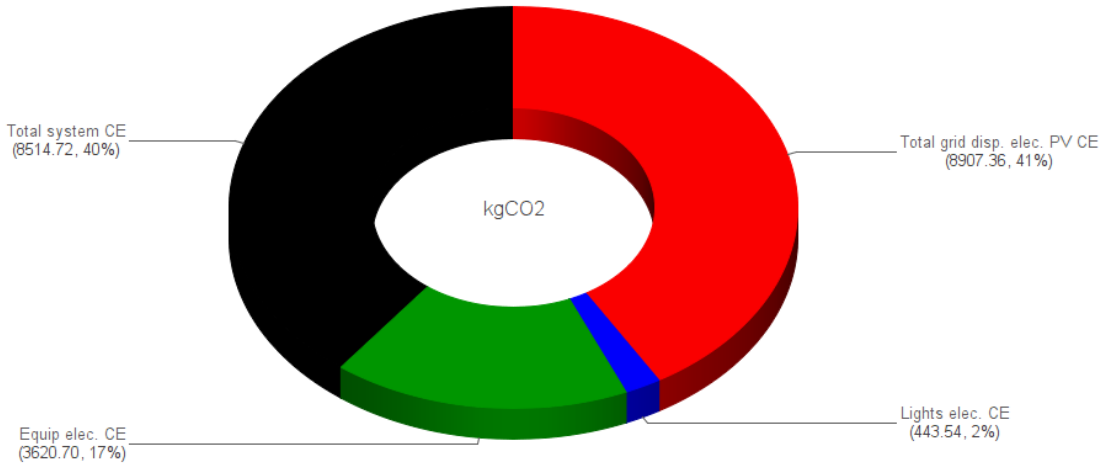


Figure 6.32 The NZEH (CO2) emissions were analysed across many categories of the whole building system, including lighting, equipment, grid PV, electricity disruption and other building systems.

As mentioned in the previous chapter, simulation for only the natural ventilation strategies helped reduce home carbon emissions (kgCO2/h) by 9.8%. On the other hand, the total energy saved from applying the NZE concept was calculated to be around 12000 kWh, which moved the base case model to operate in the net-zero-ready stage, making it feasible to install the solar panels at this stage. Moreover, according to (Almasoud & Gandayh, 2015), the total indirect expenses in Saudi Arabia are projected to be 0.1688 SR/kWh. Therefore, cutting indirect costs through regulating (GHG) emissions could save about 2000 SR each year from just a single house. As we have seen, Net Zero Energy Homes (NZEH) cut greenhouse gas (GHG) emissions by 50% by making as much energy as they use with renewable sources like solar panels. These homes reduce energy waste (GHG) by using high-efficiency envelope insulation, windows, and appliances, which means they need less fossil fuel and have a smaller carbon footprint. Net Zero Energy Homes (NZEHs) help create a sustainable future, lower utility bills and boost energy independence by making clean energy on-site. From a broader perspective, (NZEHs) make the domestic domain green and environmentally friendly by creating healthier ecosystems and sustainable communities over time.

6.6- NZE Prototype Payback Period.

The SEC has presented the methodology for determining the quantity of energy customers use via the "Consumption Tariffs" to efficiently manage user accounts and choose suitable plans based on their consumption, such as fixed bill instalment plans for all customer groups. The SEC has presented a method for determining the quantity of electricity users use through the "Consumption Tariffs" system. This allows for efficient management of user accounts and the selection of suitable plans, including fixed bill instalment plans for

all user categories. The consumption segments are measured in monthly kilowatt-hours for various types of users, such as residential, commercial, agricultural, charities, government metres, factories, and private health facilities. The details are provided in the table below (SEC, 2023). Segments are categorised based on the monthly kilowatt-hour (kWh) consumption for several types of meters, including residential, commercial, agricultural, charity, government metres, industries, and private health. The specific measurements for each segment may be found in the table below, per the SEC (2023) guidelines.

Table 6.9 New Electricity Tariffs for all building types as approved by the Council of Ministers' Decree dated 12/12/2017, which has been applied since 1/1/2018 (SEC, 2018).

Consumption categories (Kwh)	Residential (Halalah / kwh)	Commercial (Halalah / kwh)	Agricultural & Charities (Halalah / kwh)	Governmental (Halalah / kwh)	Industrial (Halalah / kwh)	Private educational facilities, private medical facilities (Halalah / kwh)
Less than 6000	18	20	16	32	18	18
More than 6000	30	30	20			

However, Saudi Arabia currently has no feed-in tariff (FIT) laws or legislation regulating renewable energy. Therefore, the financial benefits of energy conservation and reducing indirect greenhouse gas emissions on the environment will be estimated based on existing international models. Based on US market pricing, the total cost of energy production for a typical GCC utility is 12 cents per kilowatt-hour (Booz et al., 2009), equivalent to SR 0.45. In addition, solar energy economies thrive in areas with significant solar radiation potential. To make a fair comparison between solar energy and conventional production, it is essential to include the indirect costs associated with conventional electricity, encompassing environmental and health consequences. The estimated indirect expenditures in Saudi Arabia are expected to amount to 0.1688 SR/kWh, according to (Gandayh's research in 2012.).

According to the previous estimation, conserving 1 kWh will save around 0.61 SR, equivalent to the actual government electricity generation from oil and gas and reducing the environmental impact of the production.

As in the last chapter, the NZEH can produce around 17100 KWh of electricity yearly to cover and operate the prototype. On the other hand, before the enhancement and installation of renewable energy, the original base case annual energy consumption was around 30000 kWh, so the average annual cash gain will be around 18300 SR yearly. On the other hand, the cost of investment that was made previously in this chapter is around 184500 SR, which means that the consumer needs around ten years to get their money back.

$$\text{Payback Period} = \frac{\text{Cost of Investment}}{\text{Average Anual gain}} = \ proximally\ about\ 10\ years * \qquad (6.1)$$

** Note: the annual inflation rate was disregarded in this equation. Usually, the Saudi Arabia Inflation Rate fluctuates in figures between 1.5-3.5 % (trading economics, 2023).*

6.7- Summary

In the Arabian Gulf's harsh climate, our ancestors have had a critical issue coping with living in this environment. Nevertheless, they have adapted to the complex conditions by utilising some techniques extracted from their ambient environment. Those techniques (passive approaches) interact in harmony with nature rather than conflict with it, which results in moving the Indore environment to reach the thermal comfort stage without the need for any artificial source of energy. We should thus build our homes in accordance with the surrounding environment and climatic change by offering a more flexible design and a wiser selection of materials that fit our climate, much like how our ancestors managed to survive in the harsh climate of the Arabian Gulf.

Clearly, as illustrated in this chapter, by incorporating passive cooling techniques into the base case, such as natural ventilation through a wind catcher, wind scopes, and an operable door centered inside a courtyard, a home's total energy consumption is reduced by 10%, and the building's space cooling consumption (MWh) is reduced by 17%. Furthermore, the average natural ventilation (volume flow) the home receives from all geometric inlets throughout the year is approximately 4239 l/s. Regarding emissions, Natural ventilation reduced residences' carbon emissions (kgCO2/h) by 9.8%.

On the other hand, applying EEMs to the home has helped reduce its energy consumption by 30%. The most effective measure was increasing the HVAC system efficiency, which reduced total energy consumption by 24%. Moreover, enhancing the wall u-value by 50% has reduced energy consumption by 8%. To have feasible planning and design, the path towards applying the concept of NZEH begins with reducing home energy consumption before applying renewable energy strategies. Thus, reaching the stage of NZE-ready is essential before applying renewable energy. The key toward achieving the NZE stage is to combine multiple parameters, including passive cooling techniques and EEMs, enhance the building efficiency, and then utilize renewable energy.

After installing the solar panels, the result showed that the ZEH has become self-sufficient on an annual basis. The total electricity generated in the whole year from the PV system was 17.1 MWh, while the NZE-ready home consumption was roughly 16.6 MWh. Nevertheless, the solar panel system could not satisfy the total energy required in the summer months from July to December, with an average deficiency of around 7%. However, as the analysis shows, the PV system has eleven batteries with a 4.8 kw/h

capacity for each. It is better to avoid any oversizing of the system since the system is equipped with batters that can cover the minimal shortage in the summer months.

The IES modelling had a couple of limitations regarding creating the geometry and linking the windcatcher geometry with the NZEH first and second floors in the home design process. Assessing the accuracy in Identifying the wind catcher discharge openings when creating the geometry as a part entity was challenging unless the wind catcher was marked with the whole geometry for the first and second floors as one entity. When making the windcatcher a separate entity, the IES program indicates that air leakage is possible, and this is due to the windcatcher's air discharge openings. Also, regarding the Apache dynamic simulation feature, it was challenging in this investigation to make one Apache result file for two different geometries. For instance, it was limited to comparing the base case and NZEH results in one Apache result file. On the other hand, the IES program's solar panel feature is limited. Some of the solar panel selections in the library are outdated and limited, and changing some of the solar panel specifications is restricted.

CHAPTER 7

DISCUSSION AND CONCLUSION

7.1- Overview

Energy consumption in the Gulf Region has risen dramatically in recent decades as populations have grown and the residential sector has expanded. In Saudi Arabia, the construction industry is a significant energy user, especially given the region's severe hot temperature, with residential structures accounting for more than half of total energy consumption. Furthermore, the extensive use of air conditioning to cool interior areas accounts for more than 70% of total power consumption in residential structures. Since the country's power plants rely on fossil fuels, residential structures are a significant source of carbon dioxide emissions. This is exacerbated by the hot, humid atmosphere around coastal cities. Furthermore, most residential homes in the area are planned and constructed without concern for the local temperature, relying only on active mechanical cooling systems to mitigate the effects of unfavorable weather conditions. The lack of regard for passive cooling and energy-saving measures in current building construction practices has been overlooked.

This study evaluated passive cooling solutions and energy efficiency measures that might be utilised in net zero energy design and building stages. The study focused on residential houses on the east coast of the Arabian Gulf region that are responsive to the surrounding

environment and climatic conditions. During this research investigation, a conclusion and validation have been reached that NZEH in the Arabian Gulf region is an applicable concept, yet it is challenging. This requires a combination of passive cooling techniques with energy-efficient measures to reduce energy demand by at least 50% compared to the region EUI of a typical building. It is only after the implementation of renewable energy that it becomes possible to reach the NZE stage.

This chapter concludes all this research's essential findings and translates them into practical, functional recommendations for governments, architecture, and homeowners. The guidance and framework could help in general future NZE projects in hot-humid regions.

7.2- Research Outcomes

The primary research outcome is that this investigation has achieved its main aims and objectives. This study validated the ability to adopt NZE residential houses on the east coast of the Arabian Gulf region. The study has suggested reducing the energy consumption of residential buildings to reach the NZE-ready stage by implementing passive and EEMs strategies and then applying renewable energy. Thus, the applicability of this prototype was examined by performing a simulation in one of the east coast cities, Dammam, as a pathway to shift the residential building sector in the Arabian Gulf towards NZE building alternatives (see Appendix G).

Here are some of the research questions answered in this investigation.

- **How did our ancestors manage to live on the east coast of the Arabian Gulf's harsh climate without any source of electricity?**

In this severe climate region, our ancestors have had a critical issue with living in these circumstances. However, they have adapted to complex situations using passive methods from their ambient environment. Those passive approaches interact in balance with nature rather than hassle, pushing the home's space environment to reach the thermal comfort stage without any need for electricity. Our ancestors managed to live in the Arabian Gulf region without electricity by utilizing passive construction methods such as the stack Effect through wind-catchers, Thermal Mass in the use of massive walls, Cross Ventilation through Wind Scoops, Underground Temperature in the use of the basement and The Swing in Temperature Between Day and Night through courtyards, moreover, by comprehending the material's physical features, the ancient builder has decided which materials are suitable for summer or winter. For instance, coral stone is preferred in the summer. Conversely, mud bricks are used in the winter. Similarly, our ancestor passive cooling method was applied to the base case by introducing natural ventilation to the home through a wind catcher, wind scopes and an operable door, which helped reduce the building's space cooling consumption (MWh) by 17% And reduce the building's total electricity consumption (MWh) by approximately 10%.

- **What are the aspects and drawbacks related to the architectural design geometry and house envelope selection that cause elevated energy consumption in existing household buildings in Saudi Arabia?**
- Regarding home systems, As the base case energy simulations showed, the HVAC system was the dominant electricity consumer among all base case building

systems, which consumes 51% of the home's total energy. The enlargement in HVAC systems is due to building heat gain. The simulation indicated that the impact of each component on the external conduction gain directly correlates with the envelope surface area subjected to the sun. Walls are marked to be the most influencing external contributor to the HVAC loads, with an external heat gain of 62%. Moreover, exterior windows and doors contribute to the heat gain with 9% and 5%, respectively. In fact, from the disrupted survey, window glazing type is an essential factor in the building envelope. Unexpectedly, 56% of the participants reported using the single-glazing type, which allows more solar heat gain to penetrate the building.

On the other hand, Interior conduction usually occurs from resources inside the home, including people, equipment, lighting, and thermal mass from the ground floor. The investigation showed that people are observed to be the most contributor to the HVAC loads, with an interior heat gain of 60%. The heat gained from people usually depends on the number of people living in the home and the type of activities during the day.

Other secondary factors contribute to the HVAC loads, as the distributed survey showed that 21 % of building envelope homes were uninsulated, which puts more pressure on the HVAC system. Moreover, the mean for the thermostat's setback point was 23 ºC, and 19% of the users do not turn their AC system off even when the room is unoccupied, which makes the HVAC system's components work all the time, causing the home to consume more energy. As a broad picture, the base case energy consumption investigation showed that the HVAC system consumes half the total building energy demand. Moreover, since

64% of the external heat gain comes from walls, the exterior wall heat gain is the primary resource that increases the HVAC system's electricity load. So, during the house specification design process, a deep look into the HVAC system efficiency and the building envelope components, especially walls, is essential to target the most building energy consumption factors.

- **Which energy-efficient measures are most effective for the Arabian Gulf's harsh climate, and how can we move homes to a low energy consumption stage?**

Home energy efficiency can be achieved by combining strategies that vary in their capability to influence cooling load demand. Since arrangements made at different phases of the building envelope's design can affect total building energy consumption and performance, feasible planning and integration within the building envelope's design process is the solution to producing energy-efficient designs. Furthermore, selecting the most successful energy strategies requires an integrated assessment of all energy-saving measures. The combination of shading and high-performance glazing, for example, can impact the decrease of cooling load by blocking solar heat gains while lowering artificial lighting consumption by dimming or switching in response to daylight high intensity. When these criteria are considered a bundle, they are more efficient regarding energy savings and material cost feasibility. According to the findings of this investigation, using EEMs in the home helped cut energy usage by 30%. The most successful technique was increasing the efficiency of the HVAC system by 50%, which lowered overall energy use

by 24%. Furthermore, increasing the u-value of the wall by 50% reduced energy use by 8%. (see figure 7.1)

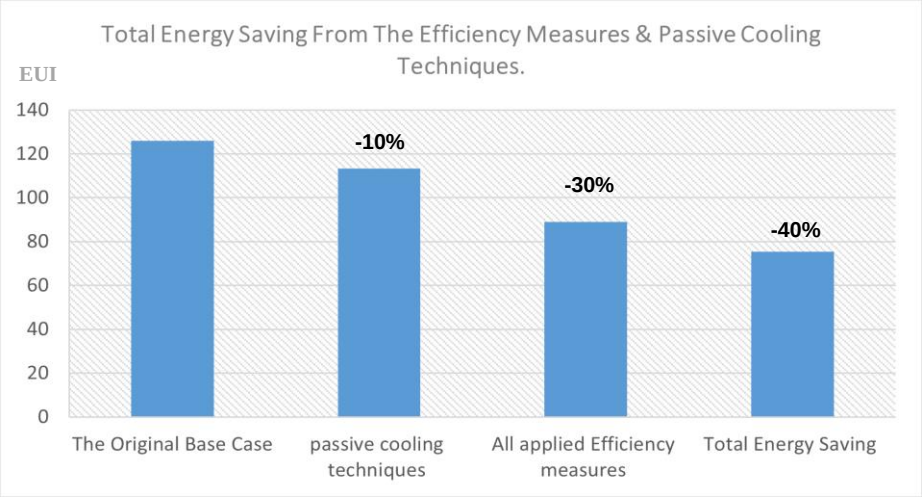


Figure 7.1 Total Energy Saving from The Efficiency Measures & Passive Cooling Techniques.

- **Is the concept of NZEH applicable in the East Coast of the Arabian Gulf region? How can Zero Energy housing be designed, and which framework can be used?**

According to this research finding, NZEH can be applied to the Arabian Gulf region, yet making this idea feasible throughout the year is challenging. The installation of solar panels made the NZEH energy simulation prototype self-sufficient annually. The total power generated by the PV system during the year was 17.1 MWh, while the NZE-ready house usage was around 16.6 MWh (see Figure 7.2). Nonetheless, the solar panel system could only meet some of the energy demand from July to December, with a shortage average of roughly 7%. Despite this minor issue, the PV system contains eleven batteries, each with a 4.8 kw/h capacity, so it is preferable to avoid oversizing the system because the batteries can cover minor insufficiency during the warmer months. To achieve realistic planning and design, the approach to implementing the NZEH idea begins with lowering household energy usage before using renewable energy applications. As a result, attaining the NZE-ready level is critical before implementing renewable. The key to reaching the NZE stage

is integrating numerous criteria, such as passive cooling techniques, EEMs, and improving building efficiency, followed by using renewable energy.

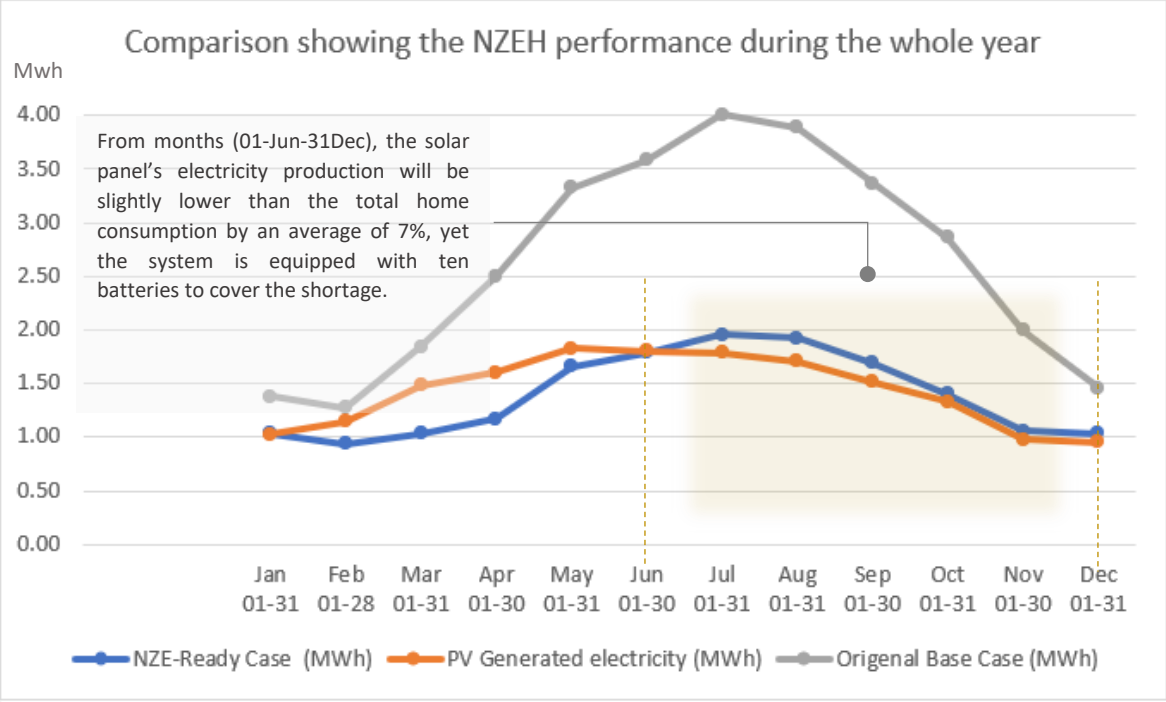


Figure 7.2 NZEH performance during the whole year shows a comparison between the electricity consumption of the base case and the NZE ready case with the PV electricity generation.

7.3-The Opportunities and Challenges to Promote NZE Residential Buildings in Saudi Arabia

As with any new movement in the community, promoting zero-energy homes in Saudi Arabia presents opportunities and challenges. This investigation was structured from scratch to make sure that the examination of a typical home was designed based on Saudi residents' desires and aspirations by distributing residential surveys followed by determining the viability of ZEHs using a simulation and modelling approach. The Gulf regions, including Saudi Arabia, have unique and extraordinary cultural conditions in terms of privacy level and home space synthesis and order, so it was essential to engage with the residents to have glams whether this kind of movement is going to be favorable to the

community or undesirable and challengeable to apply. From this research investigation findings, here are some of the opportunities and challenges affiliated with promoting zero-energy homes in Saudi Arabia:

- The Gulf region is among the most abundant solar radiation areas and the zone with the highest summer temperatures ever recorded. In Saudi Arabia, the annual irradiance in south-tilted directions can reach up to 2700 kwh\m². As shown previously in this research, solar radiation plays a significant role in the solar panels' power equation. In this research's NZE prototype, the average annual solar radiation falling on the Arabian Peninsula was 6 kWh/m²/d, which determines the solar panel's power of 9.57 kW. On the other hand, those high-temperature levels are an obstacle to solar panel efficiency. Therefore, the PV system cost and efficiency ratio under the Gulf region's severe climatic conditions is a problematic and changeable issue that must be considered.

- In the Gulf region, since there is a considerable variation in energy consumption between the summer and winter, it is challenging for the solar panels to cover the energy needs as an average for both seasons. As this investigation showed, for the selected base case, the total electricity generated in the whole year from the PV system was 17.1 MWh. In comparison, the NZE-ready home consumption was roughly 16.6 MWh. Nevertheless, the solar panel system could not satisfy the total energy required in the summer months due to the high ambient temperature that causes the HVAC system to operate all the time on summer days. Nevertheless, this issue is manageable since the NZE prototype has ten batteries with a 4.8 kw/h capacity for each that can cover the summer month average deficiency of around

7%. It is unreasonable to oversize the system to overcome this challenge since this deficiency is seasonal for only the summer months.

- Zero-energy homes can significantly reduce energy consumption and utility bills, providing long-term financial benefits for homeowners. The NZE prototype has managed to save around 18000 RS/yearly. which will be earned in positive value after ten years from the investment. Likewise, on a larger scale, governments will also ease the pressure on covering the continued demand for electricity since the government's actual electricity production price is around 0.45 SR/kw and the average consumer market price is around 0.18 SR/kw, which means the electricity prices is already subsidised by 60 %. On the other hand, the biggest challenge in this new housing movement is to convince the consumer to pay the initial cost, which was, in this research case, around 185000 RS as an added cost to the conventional base case.

- The Saudi Arabian government has shown interest in promoting renewable energy to preserve energy as one of Vision 2030 goals. Advancements in renewable energy technologies and building materials have made constructing zero-energy homes more feasible and cost-effective. Nevertheless, the absence of the NZE code and renewable energy regulation generally restricts the promotion of this movement in Saudi Arabia. Overcoming these regulatory barriers can be challenging. This was an obstacle in this research where renewable energy regulations, such as feed-in tariff (FIT), were estimated according to other international models. Moreover, developing an efficient grid infrastructure from scratch to manage the distributed

energy production from zero-energy homes is a complex project. It requires investment in grid advancements and innovative grid technologies.

- Promoting zero-energy homes aligns with Saudi Arabia's efforts to reduce greenhouse gas emissions and contain climate change, which is within the interest of the country's sustainability goals, including the 2030 Saudi vision. As shown previously in this research, promoting such reduction in CO2 conventional construction methods by adapting the NZE-housing from only a single house, could save around 2000 SR each year.

7.4- Final Recommendation & Remarks

In such a time of rising concern about energy prices, climate change, and the need to reduce carbon emissions, the concept of Net Zero Energy (NZE) residential buildings has arisen to address the high energy consumption of conventional residential buildings. Despite its massive energy resources, Saudi Arabia is not immune to global energy crises. Nonetheless, it has tremendous potential to utilize the benefits of NZE residential buildings to address environmental sustainability and economic growth.

This investigation has shown that, like how our ancestors lived in the Arabian Gulf's harsh climate without electricity, we should design our homes in conformity with the ambient surroundings and climatic change by utilizing passive approaches and EEMs that suit our environments. The obligation to reduce buildings' environmental impact, including high energy consumption, considerably relies on architects, developers, and engineers. Building construction should be responsive and adaptive to local climatic conditions and ambient environment as our ancestors' way of design. This investigation shows that the NZEH

concept could be applied in the Arabian Gulf. Architects and developers should consider utilizing passive cooling techniques in their design, which can make the home reach the NZE stage with the help of renewable energy (see table 7.1).

These research investigations and findings include the Dammam city residential survey that has been disrupted, especially for this research, and the energy simulations prototype analysis data; made a few points that should be highlighted as recommendations for applying NZEH in the region:

7.4.1- Higher Establishment's Decision-Makers

- Government support should be premier and essential in the NZE movement. Higher authority subsidizing can ensure a more feasible application of this kind of sustainable project. Proper financial support mechanisms are required to promote these homes as regular governmental support for national residential projects. This work showed that the NZEH costs 15 % more than the ordinary house, which can be earned back after ten years.

- The community's role is pivotal in the NZE movement. Without a FIT policy and clear renewable energy legislation, the payback period for such projects will be longer, making it unfeasible for individuals to invest. The government should establish FIT regulations to foster a sense of collective responsibility, allowing the whole community to rely on each other's energy production by linking them together as one large community. This collective approach is critical to the success of the NZE movement.

- This research suggests that a government loan of around 200,000 SR should be given to those who build their homes using an NZE concept that includes a solar panel system to encourage the community to utilize NZEH and renewable energy strategies in general. The government loan can be returned after ten years, which is equivalent to the NZEH payback period.

- It is crucial to Raise public awareness about home energy consumption and the benefits of reducing energy use. This research survey revealed that over 20% of individuals are unaware of their household appliances and HVAC system's energy rating cards. Additionally, 19% of users do not turn off their AC system when the room is unoccupied, and 18% do not switch off their water heating system in summer. Increasing public awareness about energy conservation can change these consumption behaviors, which is the first step towards implementing the NZE movement in the community. The government can play a significant role by implementing effective communication strategies.

7.4.2- Designers and Real Estate Developers

- Designing homes in harmony with the environment is fundamental. Designers can create energy-efficient and sustainable homes by offering a more flexible design that can adapt to climate conditions and a thoughtful selection of materials that suit our environments. This research's NZE prototype reduced the building's overall power usage (MWh) by around 10% and its space cooling consumption (MWh) by 17% by incorporating passive construction principles. This was achieved by engaging a

courtyard, wind scope, and wind catcher in the design, making these techniques work only at specific times of the year.

- Regarding the earliest designing phases of the NZEH, three main factors had crucial effects on the performance of this research NZE prototype: HVAC system efficiency, wall insulations, occupancy operation schedule, and equipment usage patterns. As this research showed, home energy consumption can be decreased 24% by increasing the efficiency of HVAC systems and 8% by enhancing the building envelope construction efficiency.

- In designing solar panel systems, avoid oversizing them; designers must begin decreasing the house's energy consumption by at least 50% lower than the average regional EUI before applying renewable energy techniques. Oversizing the solar panel system led to a more extended payback period, making it unfeasible for the tenants to engage with such sustainable homes.

- Window shading is neglected in the region; during this research site visit, most of the examined residential buildings were designed without regard for window shading. This research model simulation showed that shading the windows could increase thermal comfort and people's satisfaction by 7.2%.

7.4.3- Clients And Home Tenants

- Tenants should consistently have a strategic outlook when financing building materials over an extended period. This study demonstrated that the cost of efficient and sustainable materials is often higher than that of traditional materials. However,

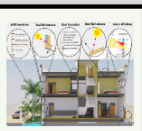
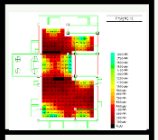
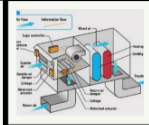
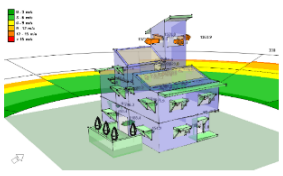
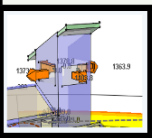
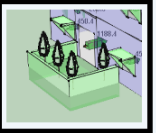
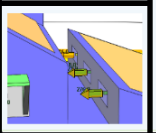
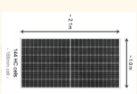
these materials are viable in the long term, particularly after the payback time has been reached. Therefore, tenants should seek expert guidance to clarify the rationale for investing in sustainable building materials, their specifications, and the time it takes to recover the investment.

- Tenants must think wisely when selecting an HVAC system. This research shows that by selecting a more efficient system, annual energy bills could be reduced by up to 24%.

- Tenants' energy consumption behaviours play a significant role in reducing electricity bills. As the distributed survey showed, 55% of the participants reported that they turn the AC system off when they go to work, which makes it challenging for the home to reach the NZE stage in the summer. Also, Setting the AC system thermostat at a higher temperature would help to reduce the cooling load on the HVAC system, as this research showed that by setting the thermostat to cool at a temperature range of 24°C-25°C, the system's energy consumption could be reduced by an additional 5%.

- When buying a new home, the clients should always ask about the building envelope specifications. This research distributed survey showed that around 25% of the participants didn't know their envelope construction type. Moreover, there were uninsulated building envelope residences with 21 %.

Table 7.1 final study investigation framework indicating the research finding & remarks coupled with each measure stage

Framework	Research Findings			Remarks
Energy Efficient Measures  **Energy Efficient Stage** In this stage, the home must be more efficient than the code compliance by 15%. The base case energy consumption efficiency was enhanced by applying some efficient and sustainable measures, which were selected depending on the analysis of the Dammam city survey and the previous literature review in this research. In this research investigation, applying EEMs to the home has helped reduce the home's energy consumption by **- 30%**.	Building Envelope	The analysis showed that increasing the base case's construction specification efficiency by +50% helped decrease the EUI by 21.5 %. Moreover, when doubling the Base case construction specification efficiency, the EUI reduces by 30.2 %.		▪ Some measures applied to the base case haven't shown any significant improvement in decreasing energy consumption. For example, reorienting the base case direction toward the north side has reduced energy consumption by 0.6%. Similarly, increasing daylighting by decreasing the reliance on artificial lights decreases energy consumption by 1.6%. ▪ Abruptly, the analysis showed that increasing the base case construction specification efficiency from +50% to +100% reduced the EUI by just 9%, which is considered a deficient percentage compared to the initial cost of increasing the building efficiency. ▪ Regarding the NZEH 's shape and orientation, the most feasible option is to redirect the base case toward the north and redesign the courtyard at the home's center.
	Day-lighting	NZEH's window distribution was rearranged to get an average of 150-200 lux in most home areas. Also, occupant-dimming profiles were added to minimize artificial lighting during the day. The result showed a minor total energy consumption reduction of 1.6%.		
	Shading Devices	The shading devices helped reduce the solar peak heat gain by 70 %. On Aug.15, The peak solar heat gain decreased from 2.7 kW to 0.9 kW after applying the shading device. Moreover, the sensible cooling load has been reduced by 8.5%.		
	HVAC Efficiency	The most effective measure was increasing the NZEH's HVAC system efficiency by +50%. The original base case SEER has increased from 3.6 to 5.4, showing a significant energy consumption reduction of 24%.		
	Shape & Orient.	The effect of changing the base case orientation on the solar heat gain was a range of 4% disparity between all elevations. The North elevation considers the feasible exposure, with. solar heat gain of around 5.8 MWh yearly		
	Set-Back point	For the original base case, the HVAC's set point is kept at 24°c during occupancy hours all year. This investigation showed that adjusting the thermostat set-back point to 24°c-25°c for cooling could offer an extra 4.8% saving in energy consumption.		
Passive cooling techniques  **Net-Zero-Ready Stage** To reach this stage, the home must consume at least around 50% less than the regional EUI. the home has been introduced to a set of passive measures that made a total reduction in energy consumption by around **- 10%**.	Wind-catcher		The base case main geometry design has been developed to re-engage the passive cooling techniques in the home. The idea behind the design is to utilize the staircase atrium to make it work as a wind catcher, which simultaneously serves as a central area to distribute the air throughout the home spaces and allow hot air to escape the building. The natural ventilation strategy works only if the room temperature is higher or equal to the outside air temperature (room temp. ≥ outside air temp.). Natural ventilation is introduced to the home through a wind catcher, wind scopes and an operable door centered inside a courtyard. After performing the simulation, the average natural ventilation throughout the year (volume flow) the house receives from all geometry inlets is around 4239 l/s. Moreover, Regarding home energy consumption in general, natural ventilation helped reduce the building's space cooling consumption (MWh) by 17% and reduce the building's total electricity consumption (MWh) by approximately 10%.	▪ Regarding building CO2 concentrations, the outside temperature is more elevated during the day than the inside, preventing natural ventilation. Hence, the high CO2 concentrations are connected directly to the absence of ventilation during noon. In fact, during noon, the CO2 consecration exceeds 1000 ppm, which might be associated with complaints of drowsiness and poor air quality. In this research, Natural ventilation helped reduce home carbon emissions (kgCO2/h) by 9.8%.
	Courtyard			
	Adobe walls			
	Wind scop			
Solar Panels systems  **Net-Zero- Stage** At this stage, after applying renewable energy, the simulation showed that NZEH has become self-sufficient annually.	Solar panels		The total NZEH home energy consumption is around 46000 w/h/day. The panel energy loss is around 5.1 kw/h/day, which sets the solar panel's power at 9.57 kW. The number of panels required = 22 panels. The inverter is 2 KW, and the loss is to be calculated by 3%, so the total energy the inverted should be supplied is around. 47.68 kw/h/day. The batteries chosen for the NZEH are lead with 90% DoD. The energy needed is 47.8 kw/h/day. So, The total battery required for the system is ten batteries. After the simulation, The IES results showed that the ZEH has become self-sufficient annually. The total electricity generated in the whole year from the PV system was 17.1 MWh, while the NZE-ready home consumption was around 16.6 MWh.	▪ The solar panel system couldn't satisfy the total energy required in the summer months from July to December, with an average deficiency of around 7%. Yet, as the analysis shows, the PV system has ten batteries with a 4.8 kw/h capacity for each. It's better to avoid oversizing the system since it is equipped with batters that can cover the minimal shortage in the summer months.
	Inventor			
	Batteries			

7.5- Research limitations

The study was influenced by factors important to the overall research objectives; nonetheless, it was constrained by limitations that restricted some of the investigations. This study has analysed the adaptation of NZEH in the Gulf area. However, the researcher experienced some limits and restrictions to the research findings throughout the research process.

- The research study investigation had some unplanned obstacles, such as the physical activities that require face-to-face interaction, which took place between 2020 and 2021 during the COVID-19 pandemic, when physical contact was limited and restricted. Some of those activities vary between using the energy simulation labs and accessing programs and data on the office computer since there was quarantine at the time. In addition, an online public survey was conducted to determine the main research topics for the residential sector. The primary constraint was the dependence on computer-based participation because of the pandemic restrictions and regulations.
- There is a lack of information in the research field of NZEH and the Operation Schedule for Usage Patterns Profiles. The region has no rules or legislation regarding NZEH (Net Zero Energy Homes) or feed-in tariffs (FIT). Quantifying the financial gains derived from positive solar panel energy production and mitigating the indirect influence of greenhouse emissions on the environment is a complex task. On the other hand, the research field has not thoroughly examined the occupancy parameters that impact total household energy consumption and

building efficiency. Most documents regarding the occupancy operating schedule in Saudi Arabia need updating.

- As part of the study, it was necessary to conduct site visits and model houses to analyse energy consumption patterns, identify design flaws in the construction and materials of the buildings, and validate the base case with actual buildings. Due to the intricate socio-cultural milieu in Saudi Arabia and the challenges in acquiring home electricity bills and architecture plans, it was challenging to include enough cases in this research since they include sensitive information. Prior authorisation from the property owners required the researcher to examine utility invoices, which was essential in validating the base case. Consequently, the researcher had to get the data from the residents of the individual properties, who in turn got the official plans and bills from the Ministry of Electricity and the Ministry of Municipality. The researcher recognises this as a constraint of the study and suggests doing more research that includes a more significant number of attributes to expand the case study sample size.

7.6- Future work

- Highly Efficient Windows

During the NZEH cost estimation investigation, unexpectedly, there was a factor that affected the total amount of the estimation. Equipping this research NZE prototype with a highly efficient triple window costs around 32000 SR for all building openings, which is approximately 20% of the total added cost budget. The technology of highly efficient windows in terms of cost, material and efficiency needs to be investigated to produce more efficient and feasible alternatives.

- Development of a Large-Scale NZE Community

This research was done on a small-scale single unit, and to validate the integration of multiple NZE units, a large-scale NZE community is a research field that needs to be investigated. This research showed a 7% solar panel energy shortage in the summer. As a community, other net zero houses could balance this kind of deficit during the year by linking them together as one large community.

- Retrofitment of Existing Dwellings

During the literature review investigation, there were a couple of retrofitment examples in the Arabian Gulf to reach the low energy consumption stage. Yet, they still needed to aim to get to the NZE stage. The retrofitment idea toward the NZE could first be initiated in the governmental buildings to encourage the community to follow their lead. Nevertheless, retrofitment building toward NZE is a new idea requiring deeper investigation regarding cost and efficiency.

- Occupancy Operation Schedule and Equipment Usage Patterns Profiles

The occupancy factors that influence the total home energy consumption and efficiency of building performance are not investigated in depth in the research field. Most papers on the occupancy operation schedule in Saudi are outdated. While designing the base case process, it was hard to validate the survey's occupancy operation, which was made especially for this research by an updated paper with a recent occupancy operation Schedule. So, more research should be done in Saudi Arabia regarding occupancy operation schedules and equipment usage patterns.

- Regional NZE Subsidizing Regulations

Since feed-in tariff (FIT) laws and legislation do not exist in Saudi Arabia currently, the amount of money earned from energy saving and reducing the indirect impact of greenhouse gases on the environment was estimated according to other international standards. More research is needed to establish NZE (FIT) lows in Saudi Arabia, especially since there isn't any complete benchmark in the region that can be relied on as a reference.

8- Reference

(A)

ABDEL-AZIM, M. S. 1997. Development of prototype structure for low-cost and energy-efficient houses by utilizing palm tree fronds. Building and Environment.

ABDUL MUJEEBU, M. & ALSHAMRANI, O. S. 2016. Prospects of energy conservation and management in buildings – The Saudi Arabian scenario versus global trends. Renewable and Sustainable Energy Reviews, 58, 1647-1663.

AFLAKI, A., MAHYUDDIN, N., AL-CHEIKH MAHMOUD, Z. & BAHARUM, M. R. 2015. A review on natural ventilation applications through building façade components and ventilation openings in tropical climates. Energy and Buildings, 101, 153-162.

AGYEKUM, K., KISSI, E., DANKU, J.C 2020. Professionals' views of vernacular building materials and techniques for green building delivery in Ghana.

AHMET VEFIK ALP 1990. Vernacular climate control in desert architecture,
Energy and Buildings, 16, 815.

AL, T. E. 2006. Zero Energy Buildings: A Critical Look at Definition.

AL., R. P. E. 2017. Natural ageing of cool walls: Impact on solar reflectance, sensitivity to thermal
Shocks and building energy needs.

AL-ABSI, Z. A., MOHD HAFIZAL, M. I., ISMAIL, M., MARDIANA, A. & GHAZALI, A. 2020. Peak indoor air temperature reduction for buildings in hot-humid climates using phase change materials. Case Studies in Thermal Engineering, 22, 100762.

ALAIDROOS 2015. Optimal design of residential building envelope systems in the Kingdom of Saudi Arabia.

ALDOSSARY, N. A., REZGUI, Y. & KWAN, A. 2017. Establishing domestic low energy consumption reference levels for Saudi Arabia and the Wider Middle Eastern Region. Sustainable Cities and Society, 28, 265-276.

ALFARIS, F., JUAIDI, A. & MANZANO-AGUGLIARO, F. 2017. Intelligent home technologies to optimize the energy performance for the net zero energy home. Energy and Buildings, 153, 262-274.

ALKHATEEB, E. & ABU-HIJLEH, B. 2019. Potential for retrofitting a federal building in the UAE to net zero

electricity building (nZEB). Heliyon, 5, e01971.

AL-MASRANI, S. M., AL-OBAIDI, K. M., ZALIN, N. A. & AIDA ISMA, M. I. 2018. Design optimization of solar shading systems for tropical office buildings: Challenges and future trends. Solar Energy, 170, 849-872.

ALOTHMAN, O. Y., JAWAID, M., SENTHILKUMAR, K., CHANDRASEKAR, M., ALSHAMMARI, B. A., FOUAD, H., HASHEM, M. & SIENGCHIN, S. 2020. Thermal characterization of date palm/epoxy composites with fillers from different parts of the tree. Journal of Materials Research and Technology, 9, 15537-15546.

ALP, A. V. 1991,. Vernacular climate control in desert architecture.

ALRASHED, F. & ASIF, M. 2015. Analysis of critical climate-related factors for applying zero-energy homes in Saudi Arabia. Renewable and Sustainable Energy Reviews, 41, 1395-1403.

AL-SAIDI, M. 2018. Green Climate Fund (GCF): Role, Capacity Building, and Directions as a Catalyst for Climate Finance.

ALTAN H, A. H. 2006. An evaluation of the total energy consumption of
educational buildings: prototype case studies in Saudi Arabia.

ASKAR, H., PROBERT, S. D. & BATTY, W. J. 2001. Windows for buildings in hot arid countries. Applied Energy, 70, 77-101.

ATALLA, T. N. & HUNT, L. C. 2016. Modelling residential electricity demand in the GCC countries. Energy Economics, 59, 149-158.

ATHIENITIS, A., AND WILLIAM O'BRIEN. 2015. Modeling, Design, and Optimization of Net-zero Energy Buildings.

AYE LU, C. W., FANDINO AM, ROBINSON JRW 2015. Thermal performance of sustainable energy features. Solar.

al, M. K. e. (2022). Residential building stock model for evaluating energy retrofit programs in Saudi Arabia - Scientific Figure on ResearchGate.

Alhawas, M. (2016). Toward net-zero residential buildings in the Arabian Gulf region (lessons learned from the Arabian Gulf vernacular architecture).

Al-Hinai. (1993). Vernacular architecture of Oman: Features that enhance thermal comfort achieved within buildings. Retrieved from https://ideas.repec.org/a/eee/appene/v44y1993i3p233-258.html

Al-Naim, M. A. (2008). Identity in Transitional Context: Open-Ended Local Architecture in Saudi Arabia.

Al-Saadi1, S. N., & , I. M. B. (2007). PERFORMANCE-BASED ENVELOPE DESIGN FOR RESIDENTIAL BUILDINGS IN HOT CLIMATES.

Al-Salem, K., Neelamani, S., & Al-Nassar, W. (2018). WIND ENERGY MAP OF ARABIAN GULF.

ASHRAE. (2009). ASHRAE Handbook - Fundamentals (SI).

ARGAAM. 2020. Available: https://www.argaam.com/en [Accessed].

ALMASOUD, A. H. & GANDAYH, H. M. 2015. Future of solar energy in Saudi Arabia. Journal of King Saud University - Engineering Sciences, 27, 153-157

(B)

BELPOLITI, V., CALZOLARI, M., DAVOLI, P., ALTAN, H. & NASSIF, R. 2020. Design optimization to enhance passive energy strategies. The KNOW HOWse project for Solar Decathlon Middle East 2018. Procedia Manufacturing, 44, 302-309.

BEN-NAKHI, A. E. & MAHMOUD, M. A. 2002. Energy conservation in buildings through efficient A/C control using neural networks. Applied Energy, 73, 5-23.

BESIR, A. B. & CUCE, E. 2018. Green roofs and facades: A comprehensive review. Renewable and Sustainable Energy Reviews, 82, 915-939.

BHAMARE, D. K., RATHOD, M. K. & BANERJEE, J. 2019. Passive cooling techniques for building and their applicability in different climatic zones—The state of art. Energy and Buildings, 198, 467-490.

BOLATTÜRK, A. 2006. Determination of optimum insulation thickness for building walls with respect to various fuels and climate zones in Turkey.

(C)

Creswell, J.. 2009. Research design: Qualitative, quantitative, and mixed approaches (3rd ed.). Los Angeles: Sage

CABEZA, L. F. & CHÀFER, M. 2020. Technological options and strategies towards zero energy buildings contributing to climate change mitigation: A systematic review. Energy and Buildings, 219, 110009.

CALAUTIT, J. K. & HUGHES, B. R. 2016. A passive cooling wind catcher with heat pipe technology: CFD, wind tunnel and field-test analysis. 162, 460-471.

CAO, V. D., PILEHVAR, S., SALAS-BRINGAS, C., SZCZOTOK, A. M., BUI, T. Q., CARMONA, M., RODRIGUEZ, J. F. & KJØNIKSEN, A.-L. 2019. Thermal analysis of geopolymer concrete walls containing microencapsulated phase change materials for building applications. Solar Energy, 178, 295-307.

CASINI, M. 2020. A positive energy building for the Middle East climate: ReStart4Smart Solar House at Solar Decathlon Middle East 2018. Renewable Energy, 159, 1269-1296.

COMPANY, P. G. A. E. 2014. ZNE-Case-Study-Buildings (1).pdf>. 138.

(D)

DARWISH, A. S. 2019. Advancements and Challenges Affecting Wind Turbine Implementation in the GCC Countries.

DE BOECK, L., VERBEKE, S., AUDENAERT, A. & DE MESMAEKER, L. 2015. Improving the energy performance of residential buildings: A literature review. Renewable and Sustainable Energy Reviews, 52, 960-975.

DENG, S., DALIBARD, A., MARTIN, M., DAI, Y. J., EICKER, U. & WANG, R. Z. 2011. Energy supply concepts for zero energy residential buildings in humid and dry climates. Energy Conversion and Management, 52, 2455-2460.

Drury B. Crawley, J. W. H., Michaël Kummert, Brent T. Griffith,. (2008). Contrasting the capabilities of building energy performance simulation programs,

EARTHSCAN 2011. A green vitruvius: principles and practice of sustainable architectural design.

EENERGY, N. 2019. Sakaka Solar Project [Online]. Available: https://www.nsenergybusiness.com/projects/sakaka-solar-project/ [Accessed].

EL-KATITI, L. 2011. Opportunities and challenges of GCC electricity market corporation.

ESHRAGHI, J., NARJABADIFAM, N., MIRKHANI, N., SADOUGHI KHOSROSHAHI, S. & ASHJAEE, M. 2014. A comprehensive feasibility study of applying solar energy to design a zero-energy building for a typical home in Tehran. Energy and Buildings, 72, 329-339

(E)

Evans. (2021). Persian Gulf. Retrieved from https://www.britannica.com/place/Persian-Gulf

(F)

FABIO FANTOZZI, C. B., CATERINA GARGARI, ROBERTO RUGANI, GIACOMO SALVADORI 2021. Do green roofs really provide significantenergy saving in a Mediterranean climate?Critical evaluation based on different casestudies.

FENG, W., ZHANG, Q., JI, H., WANG, R., ZHOU, N., YE, Q., HAO, B., LI, Y., LUO, D. & LAU, S. S. Y. 2019. A review of net zero energy buildings in hot and humid climates: Experience learned from 34 case study buildings. Renewable and Sustainable Energy Reviews, 114, 109303.

FINANCE, A. M. O. A. M. O. 2017. Energy price reform in the GCC countries

FRANCHINI 2017. design and performance predection of an energy + in Dubai. Energy procida.

FRIESS, W. A. & RAKHSHAN, K. 2017. A review of passive envelope measures for improved building energy efficiency in the UAE. Renewable and Sustainable Energy Reviews, 72, 485-496.

Fellows, R. and Liu, A. (2008). Research Methods for Construction. Wiley, 9781444309454

(G)

GAWHARY, M. 2015. كيف تعمل براجيل الهواء [Online]. Available: https://media.emaratalyoum.com/images/polopoly-inline-images/2011/06/AR30-140611-111.jpg [Accessed].

GEETHA 2012. Passive cooling methods for energy efficient buildings with and without thermal energy storage - A review. Energy Education Science and Technology Part A: Energy Science and Research, 29.

GHISI, E. & TINKER, J. A. 2005. An Ideal Window Area concept for energy efficient integration of daylight and artificial light in buildings. Building and Environment, 40, 51-61.

GILIJAMSE, W. & BOONSTRA, M. E. 1995. Energy efficiency in new houses. Heat demand reduction versus cogeneration? Energy and Buildings, 23, 49-62.

GOUDARZI, H. & MOSTAFAEIPOUR, A. 2017. Energy saving evaluation of passive systems for residential buildings in hot and dry regions. 68, 432-446.

GOV, U. 2019. Mohammed bin Rashid Al Maktoum Solar Park - a leading project that promotes sustainability in the UAE [Online]. Available: https://www.dewa.gov.ae/en/about-us/media-publications/latest-news/2019/03/mohammed-bin-rashid-al-maktoum-solar-park [Accessed].

GASTAT. (2019). governmental, residential buildings supporting programs.

Gandayh, Hatim, 2012. Appraisal of prospective schemes in solar energy applications (Masters thesis). King Abdulaziz University, Jeddah.

(H)

HALAWA, E., GHAFFARIANHOSEINI, A., GHAFFARIANHOSEINI, A., TROMBLEY, J., HASSAN, N., BAIG, M., YUSOFF, S. Y. & AZZAM ISMAIL, M. 2018. A review on energy conscious designs of building façades in hot and humid climates: Lessons for (and from) Kuala Lumpur and Darwin. Renewable and Sustainable Energy Reviews, 82, 2147-2161.

HARKOUSS, F., FARDOUN, F., BIWOLE, P.H 2018. Passive design optimization of low energy buildings in different climates.

HARRIS, M. W. J. 2002. Intelligent skins.

HASAN H, S. Y. 1998. Effect of wall's thermo-physical properties on time lagand decrement factor. Energy and Buildings.

HAWKER, R. 2008. Traditional Architecture of the Arabian Gulf : Building on Desert Tides.

HEATING, A. S. O. 1968. Refrigeration and Air Conditioning Engineers. 'ASHRAE Handbook of Fundamentals', 36-61.

Hereher, M. E. (2020). Assessment of Climate Change Impacts on Sea Surface Temperatures and Sea Level Rise—The Arabian Gulf. Climate, 8(4), 50

Hijazi, J (2018). Towards Displacing Domestic Air Conditioning in KSA. Doctoral dissertation. University of Strathclyde, Glasgow, United Kingdom.

(K)

KHALILI, M. & AMINDELDAR, S. 2014. Traditional solutions in low-energy buildings of hot-arid regions of Iran. Sustainable Cities and Society, 13, 171-181.

KHAN, M. J. A. I., M. T. 2004. 04/02452 Wind energy resource map of Newfoundland. Fuel and Energy Abstracts, 45, 343.

KIRIMTAT, A., KOYUNBABA, B. K., CHATZIKONSTANTINOU, I. & SARIYILDIZ, S. 2016. Review of simulation modelling for shading devices in buildings. Renewable and Sustainable Energy Reviews, 53, 23-49.

KRISTIANSEN, A. B., MA, T. & WANG, R. Z. 2019. Perspectives on industrialized transportable solar powered zero energy buildings. Renewable and Sustainable Energy Reviews, 108, 112-124.

KUCZYŃSKI, T. & STASZCZUK, A. 2020. Experimental study of the influence of thermal mass on thermal comfort and cooling energy demand in residential buildings. Energy, 195, 116984.

(L)

LAN, L., WOOD, K. L. & YUEN, C. 2019. A holistic design approach for residential net-zero energy buildings: A case study in Singapore. Sustainable Cities and Society, 50, 101672.

LATHROP, O. 2019. Why Should You Consider Solar Panel Cleaning [Online]. Available: https://www.homeandgardenwithdonna.com/why-should-you-consider-solar-panel-cleaning.html [Accessed].

LECHNER, N. 2014 Heating, Cooling, Lighting: Sustainable Design Methods for Architects.

LEE, J. W., JUNG, H. J., PARK, J. Y., LEE, J. B. & YOON, Y. 2013. Optimization of building window system in Asian regions by analyzing solar heat gain and daylighting elements. Renewable Energy, 50, 522-531.

LI, D. H. W., YANG, L. & LAM, J. C. 2013. Zero energy buildings and sustainable development implications – A review. Energy, 54, 1-10.

LIU, S., KWOK, Y. T., LAU, K. K.-L., OUYANG, W. & NG, E. 2020. Effectiveness of passive design strategies in responding to future climate change for residential buildings in hot and humid Hong Kong. Energy and Buildings, 228, 110469.

LUIS PÉREZ-LOMBARD, J. O., ISMAEL R. ORTIZ, JUAN F. 2012. Maestre, Coronelconstructing HVAC energy efficiency indicators, Energ Build.

(M)

M. SHIVAKUMAR, T. S. 2020. Characterization study on the influence of limestone and shell lime as a fine aggregate substitute: A traditional approach on lime plaster restoration.

M.R. SUDHIR, M. B., P. SASHA RAI, G. GAYATHRI, 2020. A microstructure exploration and compressive strength determination of red mud bricks prepared using industrial wastes,

MACLAY, B. 2014. The New Net Zero: Leading-edge Design and Construction of Homes and Buildings for a Renewable Energy Future.

MAO, J., YANG, W. & GAO, N. 2015. The transport of gaseous pollutants due to stack and wind effect in high-rise residential buildings. Building and Environment, 94, 543-557.

MATTHEOS SANTAMOURIS, D. K. 2013. Passive cooling dissipation techniques for buildings and other structures: The state of the art, Energy and Buildings, 57.

MAZUMDER, M. K. 2015. Electrodynamic removal of dust from solar mirrors and its applications in concentrated solar power (CSP) plants.

MD. ALAM HOSSAIN MONDAL, D. H., SCOTT KENNEDY, TOUFIC MEZHER 2016. The GCC countries RE-readiness: Strengths and gaps for development of renewable energy technologies, Renewable and Sustainable Energy Reviews, 54.

MEREDITHGRAY 2011. Energy, Sustainability and the Environment, Chapter 9 - Getting to Zero: Green Building and Net Zero Energy Homes. Pages 231-271.

MOKRZECKA, M. 2018. Influence of building shape and orientation on heating demand: simulations for student dormitories in temperate climate conditions. E3S Web of Conferences, 44, 00117.

MORAKINYO, T. E., DAHANAYAKE, K. W. D. K. C., NG, E. & CHOW, C. L. 2017. Temperature and cooling demand reduction by green-roof types in different climates and urban densities: A co-simulation parametric study. Energy and Buildings, 145, 226-237.

Monawar. (2001). A Study of Energy Conservation in the Existing Apartment Buildings in Makkah Region, Saudi Arabia.

Moncef Krartia, K. D., and Nicholas Howarthb. (2019). Energy Productivity Analysis Framework for Buildings: A Case Study of the GCC Region.

(N)

NC, B. 1993. . Benefits of energy-efficient lighting.

NIACHOU A, P. K., SANTAMOURIS M, TSANGRASSOULIS A,MIHALAKAKOU G 2001. . Analysis of the Green roof thermal properties and investiga-tion of its energy performance. Energy and Buildings.

(O)

ORBEN V. ESBENSEN, V. K. 1977. Dimensioning of the solar heating system in the zero energy house in Denmark.

(P)

PEFFER, T., PRITONI, M., MEIER, A., ARAGON, C. & PERRY, D. 2011. How people use thermostats in homes: A

review. Building and Environment, 46, 2529-2541.

PICARD, T., HONG, T., LUO, N., LEE, S. H. & SUN, K. 2020. Robustness of energy performance of Zero-Net-Energy (ZNE) homes. Energy and Buildings, 224.

PISELLO, A. L. 2015. High-albedo roof coatings for reducing building cooling needs. Elsevier.

PRAVEEN, R. P., KELOTH, V., ABO-KHALIL, A. G., ALGHAMDI, A. S., ELTAMALY, A. M. & TLILI, I. 2020. An insight to the energy policy of GCC countries to meet renewable energy targets of 2030. Energy Policy, 147, 111864.

(R)

R.P. PRAVEEN, V. K., AHMED G. ABO-KHALIL, ALI S. ALGHAMDI, ALI M. ELTAMALY, ISKANDER TLILI, 2020. An insight to the energy policy of GCC countries to meet renewable energy targets of 2030. 147.

RADHI, H. 2011. On the value of decentralised PV systems for the GCC residential sector. Energy Policy, 39, 2020-2027.

RODRIGUEZ-UBINAS, E., MONTERO, C., PORTEROS, M., VEGA, S., NAVARRO, I., CASTILLO-CAGIGAL, M., MATALLANAS, E. & GUTIÉRREZ, A. 2014. Passive design strategies and performance of Net Energy Plus Houses. Energy and Buildings, 83, 10-22.

RUNSHENG TANG, Y. E. 2005. Cooling performance of roof ponds with gunny bags floating on water surface as compared with a movable insulation, Renewable Energy, 30.

Rodrigu, E. (2016). Calculate the LED Lumens You'll Need To Light Your Space.

(S)

SABIE, K. K. E. A. 2014. Sustainability Assessment Methods for the Gulf Region.

SAKIYAMA, N. R. M., CARLO, J. C., FRICK, J. & GARRECHT, H. 2020. Perspectives of naturally ventilated buildings: A review. Renewable and Sustainable Energy Reviews, 130, 109933.

SARı, A. & KARAIPEKLI, A. 2007. Thermal conductivity and latent heat thermal energy storage characteristics of paraffin/expanded graphite composite as phase change material. Applied Thermal Engineering, 27, 1271-1277. SBC 2015. energy section.

SCHOONENBOOM, J. & JOHNSON, R. B. 2017. How to Construct a Mixed Methods Research Design. KZfSS Kölner Zeitschrift für Soziologie und Sozialpsychologie, 69, 107-131.

SHIN, M., BALTAZAR, J.-C., HABERL, J. S., FRAZIER, E. & LYNN, B. 2019. Evaluation of the energy performance of a net zero energy building in a hot and humid climate. Energy and Buildings, 204, 109531.

SISMAN, N., KAHYA, E., ARAS, N. & ARAS, H. 2007. Determination of optimum insulation thicknesses of the external walls and roof (ceiling) for Turkey's different degree-day regions. Energy Policy.

SONS, J. W. 2009. Heating, cooling, lighting: sustainable design methods for architects.

SOUBDHAN T, F. T., BADE F 2005. Experimental evaluation of insulation mate-rial in roofing system under tropical climate. Solar Energy.

STATISTICS, K. O. S. A. G. T. O. 2019. Housing Statistics Bulletin.

STRAUBE, J. 2001. HighR-value enclosures for high performance residentialbuildings in all climate zones.

SUDHAKAR, K., WINDERL, M. & PRIYA, S. S. 2019. Net-zero building designs in hot and humid climates: A state-of-art. Case Studies in Thermal Engineering, 13.

SUDHAKAR, K., WINDERL, M. & PRIYA, S. S. 2019. Net-zero building designs in hot and humid climates: A state-of-art. Case Studies in Thermal Engineering, 13, 100400.

sakani. (2020). "Sakani "residential program.

SBC. (2018). Saudi Energy Conservation Code. In.

SEC. (2018). Electricity Tariffs.

Shuaiby, A. M. (1972). The development of the Eastern Province, with particular reference to urban settlement and evolution in eastern Saudi Arabia.

Statistics, G. A. o. (2010). Saudi Arabia Census 2010.

DEHGHANI-SANIJ, A. R., SOLTANI, M. & RAAHEMIFAR, K. 2015. A new design of wind tower for passive ventilation in buildings to reduce energy consumption in windy regions. Renewable and Sustainable Energy Reviews, 42, 182-195.

(T)

TALEB, H. M. 2014. Using passive cooling strategies to improve thermal performance and reduce energy consumption of residential buildings in U.A.E. buildings. Frontiers of Architectural Research, 3, 154-165.

TALEB, H. M. & PITTS, A. C. 2009. The potential to exploit use of building-integrated photovoltaics in countries of the Gulf Cooperation Council. Renewable Energy, 34, 1092-1099.

THOMAS, W. D. & DUFFY, J. J. 2013. Energy performance of net-zero and near net-zero energy homes in New England. Energy and Buildings, 67, 551-558.

TIMILSINA, G. R., KURDGELASHVILI, L. & NARBEL, P. A. 2012. Solar energy: Markets, economics and policies. Renewable and Sustainable Energy Reviews, 16, 449-465.

TIS-MTL-ALI 2009. Solar Reflectance, Thermal Emittance and Solar Reflectance Index (SRI) .

TOE, D. H. C. & KUBOTA, T. 2015. Comparative assessment of vernacular passive cooling techniques for improving indoor thermal comfort of modern terraced houses in hot–humid climate of Malaysia. Solar Energy, 114, 229-258.

TORCELLINI, S. P. A. P. Net-Zero Energy Buildings: A Classification System Based on Renewable Energy Supply Options.

TOUATI 2012. Towards understanding the effects of climatic and environmental factors on solar PV performance in arid desert regions (Qatar) for various PV technologies.

(U)

UNION, O. J. O. T. E. 2011. he European Parliamentand of the Council with regard to energy labelling of air conditioners.

(V)

VAHID VAKILOROAYA, B. S., AHMAD FAKHAR, KAMBIZ PISHGHADAM 2014. , Areview of different strategies for HVAC energy saving.

(W)

WAHID, M. A., HOSSEINI, S. E., HUSSEN, H. M., AKEIBER, H. J., SAUD, S. N. & MOHAMMAD, A. T. 2017. An overview of phase change materials for construction architecture thermal management in hot and dry climate region. Applied Thermal Engineering, 112, 1240-1259.

WILLIS, J. 2015. Fast Forwards: 10 Years of Sustainable Initiatives in the Gulf Region. Architectural Design, 85, 114-119.

(Z)

ZEINEB ABDMOULEHN, R. A. M. A., ADEL GASTLI 2014. Recommendations on renewable energy policies for the GCC countries

ZINZI, M. 2016. Exploring the potentialities of cool facades to improve the thermal response of Mediterranean residential buildings.

Zhu, D., Hong, Tianzhen, Yan, Da, and Wang, Chuang. (2012).Comparison of Building Energy Modeling Programs.

9- Appendix

Appendix A: Dammam City Residential Building Survey

Q1. What is the type of your current dwelling?

o Apartment o Villa o Duplex

o Traditional House o Other (Please specify) _____

Q2.What is the area (in square meter) of your current dwelling?

o <300 o 300-400 o 401 - 500 o 501 -600

o 601 -700 o 701 -800 o 801 -900 o >900

Q3. What is the tenure type of your current dwelling?

o Rented o Owned o work related Accommodation

o Other (Please specify) _____

Q4. What is the construction period of your current dwelling?

o Before 1960 o 1960-1970 o 1971-980 o 1981-1990

o 1991-2000 o 2001-2010 o 20011-present o Unknown

Q5. How did you Financed the period of your current dwelling?

o Savings o Loans o Savings and Loans

o Monthly income (for rented dwelling) o Other (Please specify) _____

Q6. How many floors (stories) does your current dwelling have?

o 1 o 2 o 3 o 4

Q7. What type of spaces does your current dwelling has, and how many of them are there?

Functional space	None	1	2	3	4	**5**	> 5
Bedroom	o	o	o	o	o	o	o
Living room	o	o	o	o	o	o	o
Men guestroom	o	o	o	o	o	o	o
Women guestroom	o	o	o	o	o	o	o
Dining room	o	o	o	o	o	o	o
Internal kitchen	o	o	o	o	o	o	o
External kitchen	o	o	o	o	o	o	o
Office	o	o	o	o	o	o	o

Multi-purpose room	o	o	o	o	o	o	o
Laundry	o	o	o	o	o	o	o
Bathrooms/toilets	o	o	o	o	o	o	o
Storage	o	o	o	o	o	o	o
Maid's room	o	o	o	o	o	o	o
Driver room	o	o	o	o	o	o	o

Q8. How do you cool your current dwelling during summer (Select all that apply)?

 o Evaporative Cooler System	 o Window-Type System	 o Package Unit System
 o Mini-Split Unit System	 o Chilled Water Ssystem	

Q9. How do you heat your current dwelling during winter (Select all that apply)?

 o Halogen Heating Device	 o Oil-Filled Radiator	 o Package Unit System
 o Mini-Split Unit System	 o Window-Type System	

Q10. What types of artificial lighting system do you use for indoor lighting within your current dwelling (Select all that apply)?

 o Incandescent	 o Tubular Fluorescent
 o Compact Fluorescent	 o Tungsten-Halogen

Q11. What type of external walls (building envelope) do you have in your current dwelling?

o Single Block Wall o Insulated Single Block Wall

o Insulated Cavity Wall (Sandwich) o Lightweight Block (siporex)

o Terracotta Brick o Other (Please specify) _____

Q12. What type of glazing is used for window in your current dwelling?

o Single-Glazed o Double-Glazed

o Triple-Glazed o Unknown

Q13. What is your average monthly summer electricity bills ?

o <500 SR	o 501-700SR	o 701-900SR	o 901-1100 SR
o 1101-1300 SR	o 1301-1500 SR	o 1501-1700SR	o 1701-1900 SR
o 1901-2100 SR	o 2101-2300SR	o 2301-2500 SR	o >2500 SR

Q14. What is your average monthly winter electricity bills ?

o <500 SR	o 501-700SR	o 701-900SR	o 901-1100 SR
o 1101-1300 SR	o 1301-1500 SR	o 1501-1700SR	o 1701-1900 SR
o 1901-2100 SR	o 2101-2300SR	o 2301-2500 SR	o >2500 SR

Q15. Are you aware of the energy rating of your HVAC system and appliances?

o Yes, All of them

o Yes, Most of them

o Yes, Some of them

o Not at all

Q16. To what extent do you accept paying around 30% more initial cost for an NZEH dwelling if you get the money back in a certain payback period?

o Highly Acceptable

o Acceptable

o Do not mind

o Unacceptable (Why?) _____

Q17. To what extent do you accept Photovoltaic panels for electricity generation integrated with your future dwelling?







o Highly Acceptable

o Acceptable

o Do not mind

o Unacceptable (Why?) _____

Q18. To what extent do you accept a micro wind turbine for electricity generation integrated with your future dwelling?





o Highly Acceptable o Acceptable

o Do not mind o Unacceptable (Why?) _____

Q19. To what extent do you accept a courtyard with a fountain in your future dwelling for the sake of cooling?





o Highly Acceptable o Acceptable

o Do not mind o Unacceptable (Why?) _____

Q20. To what extent do you accept natural ventilation introduced by wind towers in your future dwelling?





o Highly Acceptable o Acceptable

o Do not mind o Unacceptable (Why?) _____

Q21. To what extent do you accept vegetation on the roof of your future dwelling?





o Highly Acceptable o Acceptable

o Do not mind o Unacceptable (Why?) _____

Q22. How old are you?

o 18-23	o 24-29	o 30-35	o 36-41
o 42-47	o 48-53	o 54-59	o >60

Q23. What is your gender?

o Male o Female

Q24. What is your marital status?

o Married o Unmarried

Q25. What is the number of your house family members? (including you)

o 1	o 2	o 3	o 4
o 5	o 6	o 7	o 8
o 9	o 10	o 11	o >11

Q26.What is your current educational level?

o Non-educated o Elementary o Intermediate

o High School o Diploma o Postgraduate Degree

Q27.What is your current profession?

o Unemployed o Student o Government employee

o Private employee o Entrepreneur o Retired

Q28.What is your monthly income?

o <4000 SR o 4001-6000 SR o 6001-8000 SR o 8001-10000 SR

o 10001-12000 SR o 12001-1400 SR o 14001-16000 SR o 16001-18000 SR

o 18001-20000 SR o 20001-22000 SR o 22001-25000 SR o > 25000 SR

Q29. What is your profession?

o Architect o Engineer

o Project Manager o Construction Contractor

o Developer and Investor o Other- Please specify _____

Q30. How many years of experience do you have in your field of work?

o <5 Years o 5-10 Years

o 11-15 Years o 16-20 Years

o >20 Years

Q31. What are the main types of building projects that you have experience with (Select all that apply)?

o Residential buildings o Commercial buildings

o Educational buildings o Governmental buildings

o Industrial buildings o Other- Please specify _____

Q32. How would you prioritize the followings in any projects (allocate a number from 1 to 7 against the options where 1 stands for highest priority and 7 for least importance)

o Cost _____ o Quality and durability____ o Modernity _____

o Sustainability & environmental friendly _____ o Renewable Energy

o project schedule and time managements_____ o Safety

Q33. How deep is the thermal insulation of the external walls in most of projects that you have exposed to ?

o None o 25mm (1") o 50mm (2") o 75mm (3")

o 100mm (4") o 150mm (6") o >150mm (6") o Unknown

o Other- Please specify_____

Q6.What type of glazing is used for windows in most of projects that you have exposed to ?

o Single-glazed o Double-glazed

o Triple-glaze o Unknown

Q34. Did you consider any of these concepts in your previous and current projects (Select all that apply)?

o Energy-saving measures o Renewable energy applications

o Sustainable design features o passive cooling techniques

o None

Q35.To what extent do you think these environmental energy measures are important for the sake of energy conservation?

Measures	Extremely Important	Substantially Important	Moderately Important	Marginally Important	Unimportant
Windcatcher	o	o	o	o	o
Courtyard	o	o	o	o	o
Shading Devices	o	o	o	o	o
Day Lighting	o	o	o	o	o
Green Roof	o	o	o	o	o
Phase Change Materials	o	o	o	o	o
HVAC Efficiency	o	o	o	o	o
Thermostat Setback	o	o	o	o	o

Q36.To what extent do you think that individual will accept to pay around 30% more initial cost for an Net-Zero-Energy dwelling if they get the money back in a certain payback period?

o Highly Acceptable o Acceptable

o Rarely Acceptable o Unacceptable (Why?) _____

Q37. Do you think that the Saudi residential market is ready to adapt the concept of Zero Energy Buildings and the application of renewable energy?

o it's ready now o needs from1-2 years to be ready

o needs from 3-5 years to be ready o needs from 6-8 years to be ready

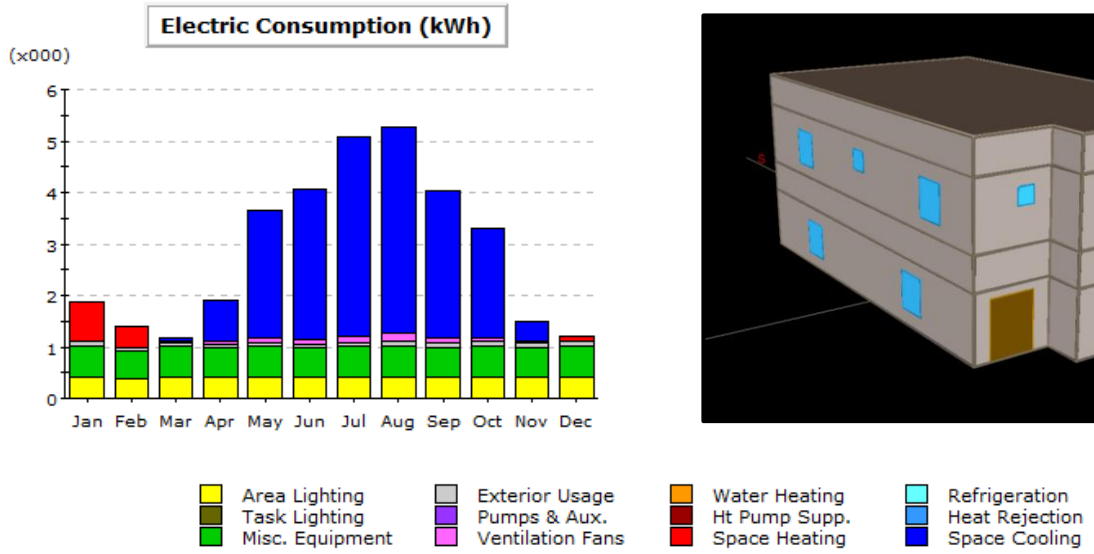
o needs more than 10 years to be ready

Q38. To what extent do you think these obstacles will prevent the application of zero energy buildings and the utilization of renewable energy resources in Saudi Arabia?

Constraint	Major Constraint	Minor Constraint	Not a Constraint
Lack of public awareness on sustainable buildings.	o	o	o
Lack of awareness and interest from designers and developers to promote sustainable buildings.	o	o	o
Lack of interest and awareness from governmental authorities to promote sustainable buildings.	o	o	o
Absence of regulations and policies in terms of sustainable buildings.	o	o	o
Sustainable design features are too expensive or not affordable.	o	o	o
Lack of related infrastructure that support the movement toward utilizing renewable energy.	o	o	o

o Other- Please specify_____

Appendix B: Dammam City Residential Building eQuest energy modelling & validation data.

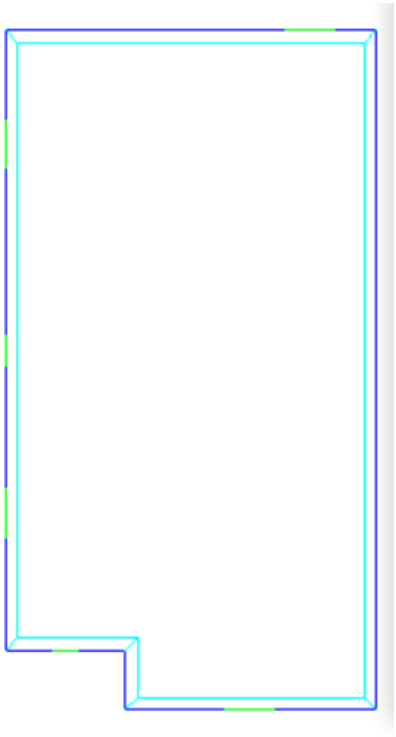


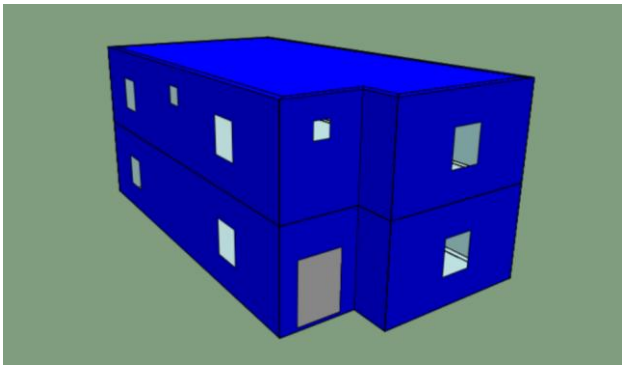
Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	-	-	0.09	0.81	2.49	2.90	3.86	4.01	2.85	2.11	0.40	0.01	19.54
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	0.75	0.39	-	-	-	-	-	-	-	-	0.01	0.09	1.23
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	-	-	-	-	-	-	-	-	-	-	-	-	-
Vent. Fans	0.02	0.01	0.01	0.04	0.10	0.11	0.14	0.16	0.11	0.08	0.03	0.00	0.80
Pumps & Aux.	0.01	0.00	-	-	-	-	-	-	-	-	-	0.00	0.01
Ext. Usage	0.09	0.07	0.07	0.07	0.05	0.05	0.05	0.08	0.08	0.08	0.08	0.09	0.86
Misc. Equip.	0.60	0.55	0.61	0.59	0.60	0.59	0.60	0.60	0.58	0.60	0.58	0.60	7.11
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	0.41	0.37	0.41	0.40	0.41	0.40	0.41	0.41	0.40	0.41	0.40	0.41	4.87
Total	1.87	1.38	1.18	1.91	3.66	4.05	5.08	5.27	4.02	3.29	1.50	1.21	34.43

Figure A1. electric consumption for Dammam city residential building, eQuest energy modelling and validation data.

Appendix C: Dammam City Residential Building IES energy modelling validation data.





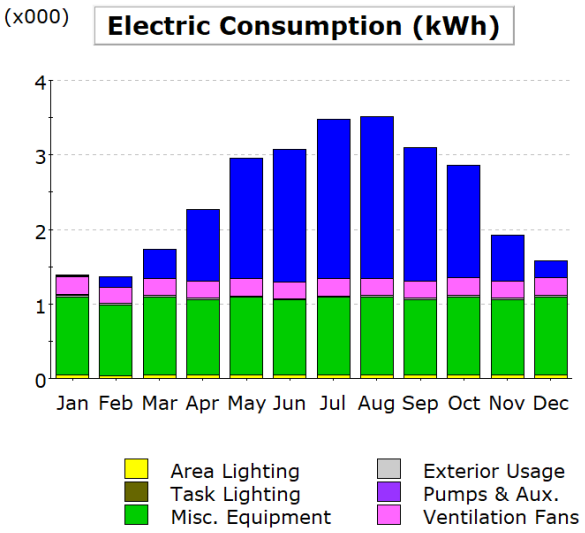
Σh Chart(1): Fri 01/Jan to Fri 31/Dec

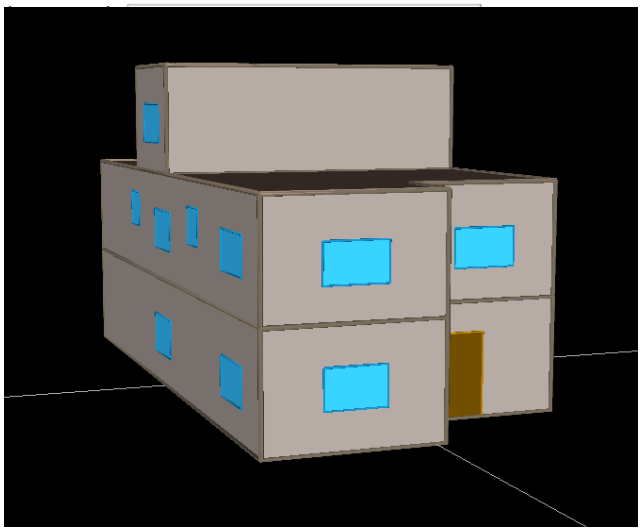
Output Analysis Help

	Total energy (MWh)
Date	validation last try.aps
Jan 01-31	0.9342
Feb 01-28	0.4559
Mar 01-31	0.5278
Apr 01-30	1.8439
May 01-31	3.6868
Jun 01-30	5.0011
Jul 01-31	5.5716
Aug 01-31	5.4712
Sep 01-30	4.5410
Oct 01-31	3.2287
Nov 01-30	0.9424
Dec 01-31	0.6833
Summed total	32.8879

Figure A2. Dammam City Residential Building IES energy modelling validation data.

Appendix D: The Base case energy simulation model for IES & equest.





Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	0.02	0.14	0.39	0.97	1.62	1.78	2.14	2.16	1.79	1.51	0.62	0.23	13.37
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	0.01	0.00	-	-	-	-	-	-	-	-	-	0.00	0.01
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	-	-	-	-	-	-	-	-	-	-	-	-	-
Vent. Fans	0.23	0.21	0.23	0.22	0.23	0.22	0.23	0.23	0.22	0.23	0.22	0.23	2.72
Pumps & Aux.	0.02	0.01	-	-	-	-	-	-	-	-	-	0.00	0.03
Ext. Usage	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.03	0.03	0.03	0.27
Misc. Equip.	1.05	0.94	1.05	1.01	1.05	1.01	1.05	1.05	1.01	1.05	1.01	1.05	12.31
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.52
Total	1.39	1.36	1.74	2.27	2.96	3.07	3.48	3.51	3.09	2.86	1.93	1.58	29.24

Figure A3. The Base case energy simulation model.

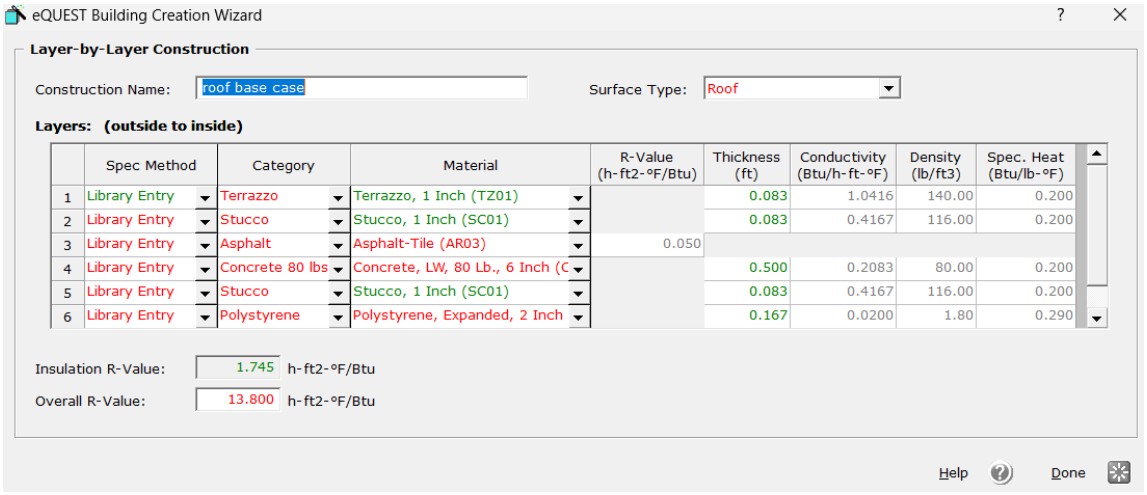


Figure A4. The Base case roof construction layers

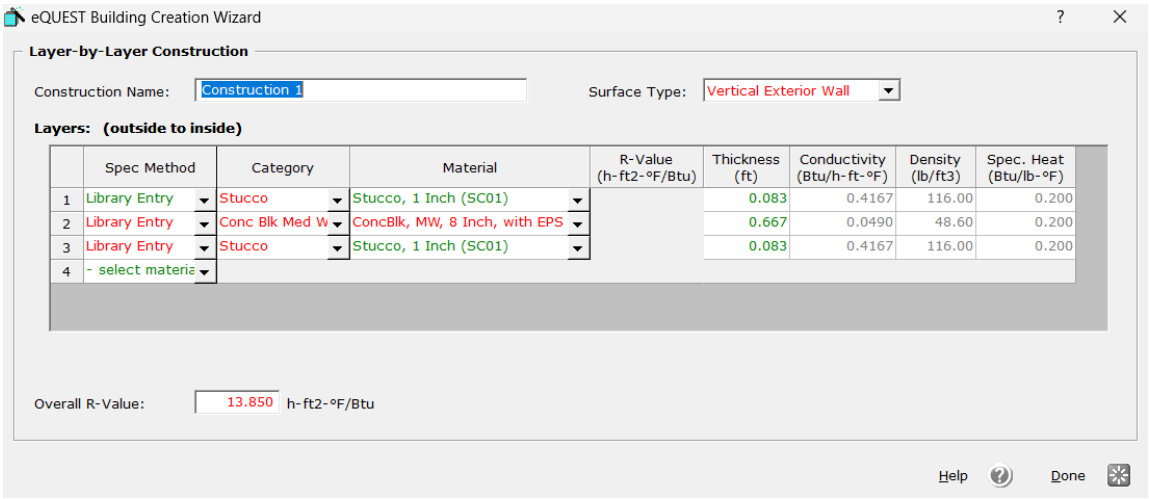


Figure A5. The Base case wall construction layers

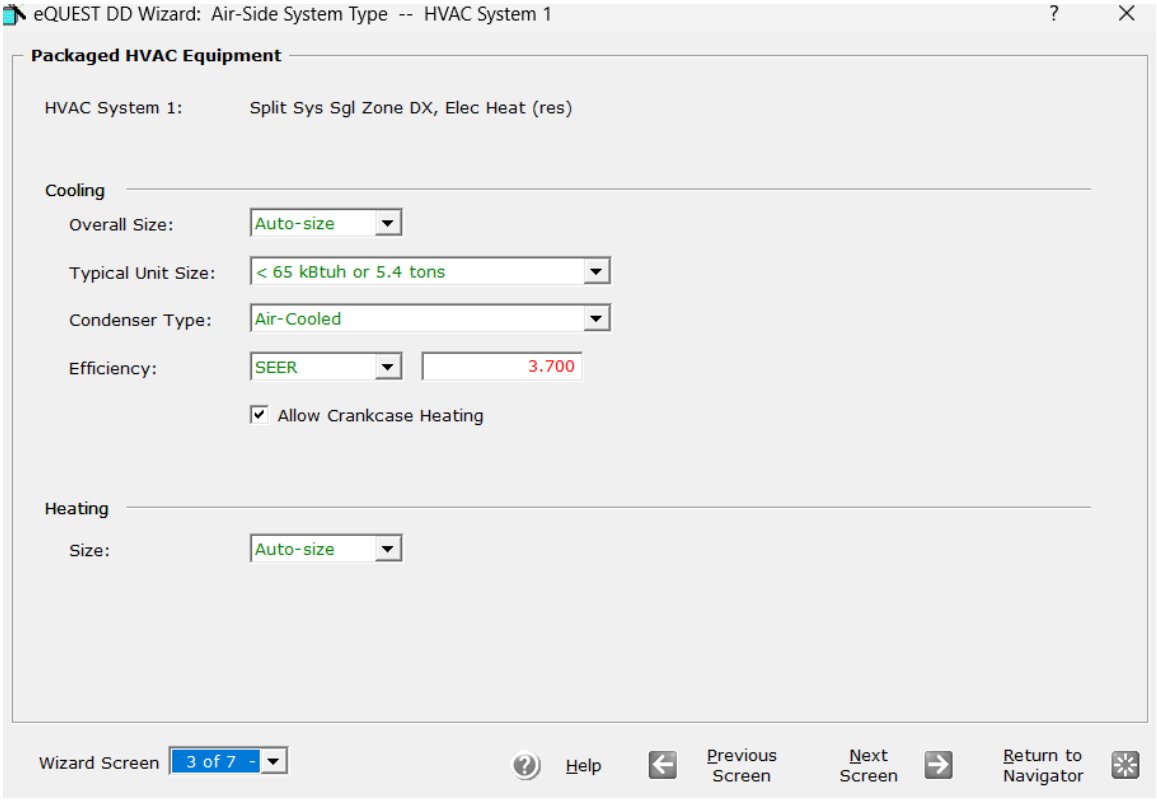


Figure A6. The Base case HVAC specification.

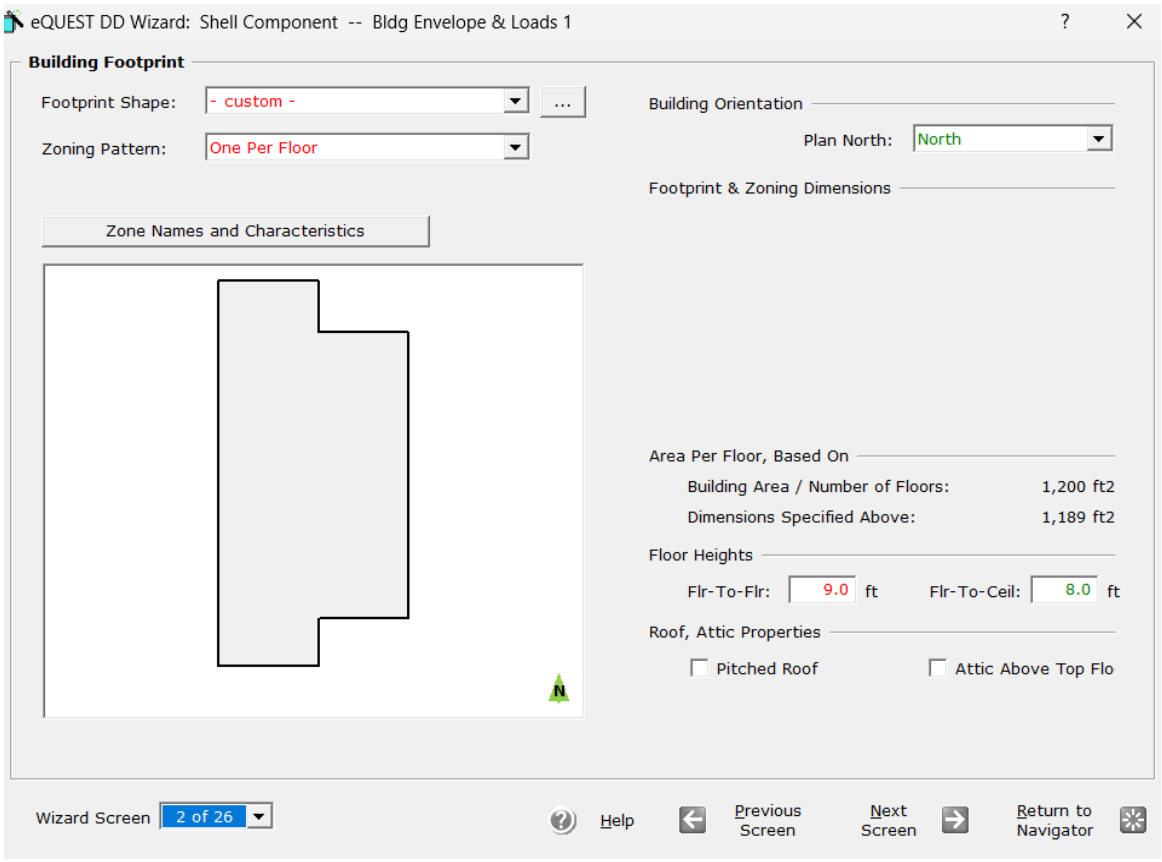
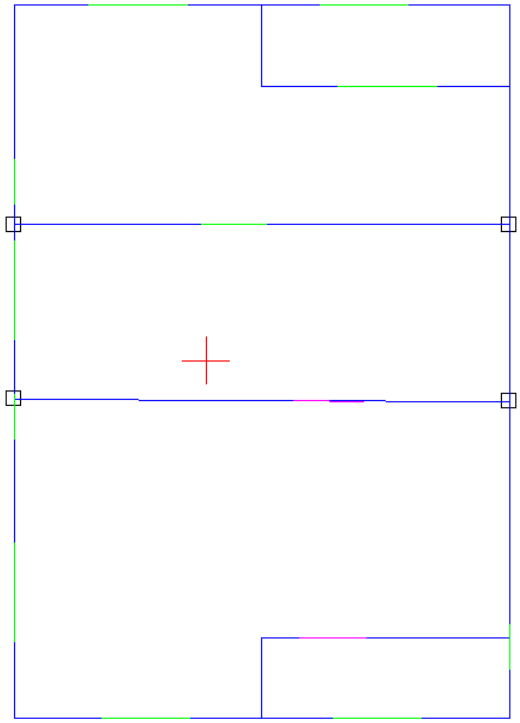
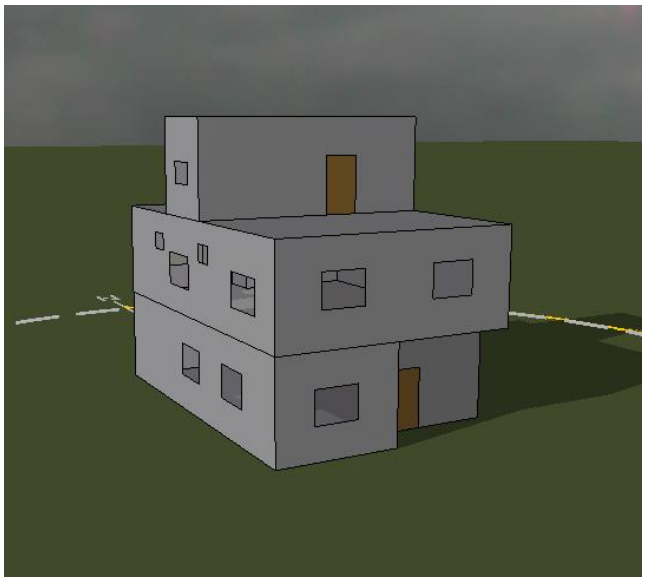


Figure A7. The Base case building footprint.





Chart(1): Sun 01/Jan to Sun 31/Dec

Output Analysis Help

	Total energy (MWh)
Date	
Jan 01-31	1.4394
Feb 01-28	1.2748
Mar 01-31	1.8442
Apr 01-30	2.4984
May 01-31	3.3282
Jun 01-30	3.5806
Jul 01-31	4.0123
Aug 01-31	3.8924
Sep 01-30	3.3701
Oct 01-31	2.8630
Nov 01-30	1.9997
Dec 01-31	1.4946
Summed total	31.5979

Figure A8. The Base case IES model energy consumption and building geometry.

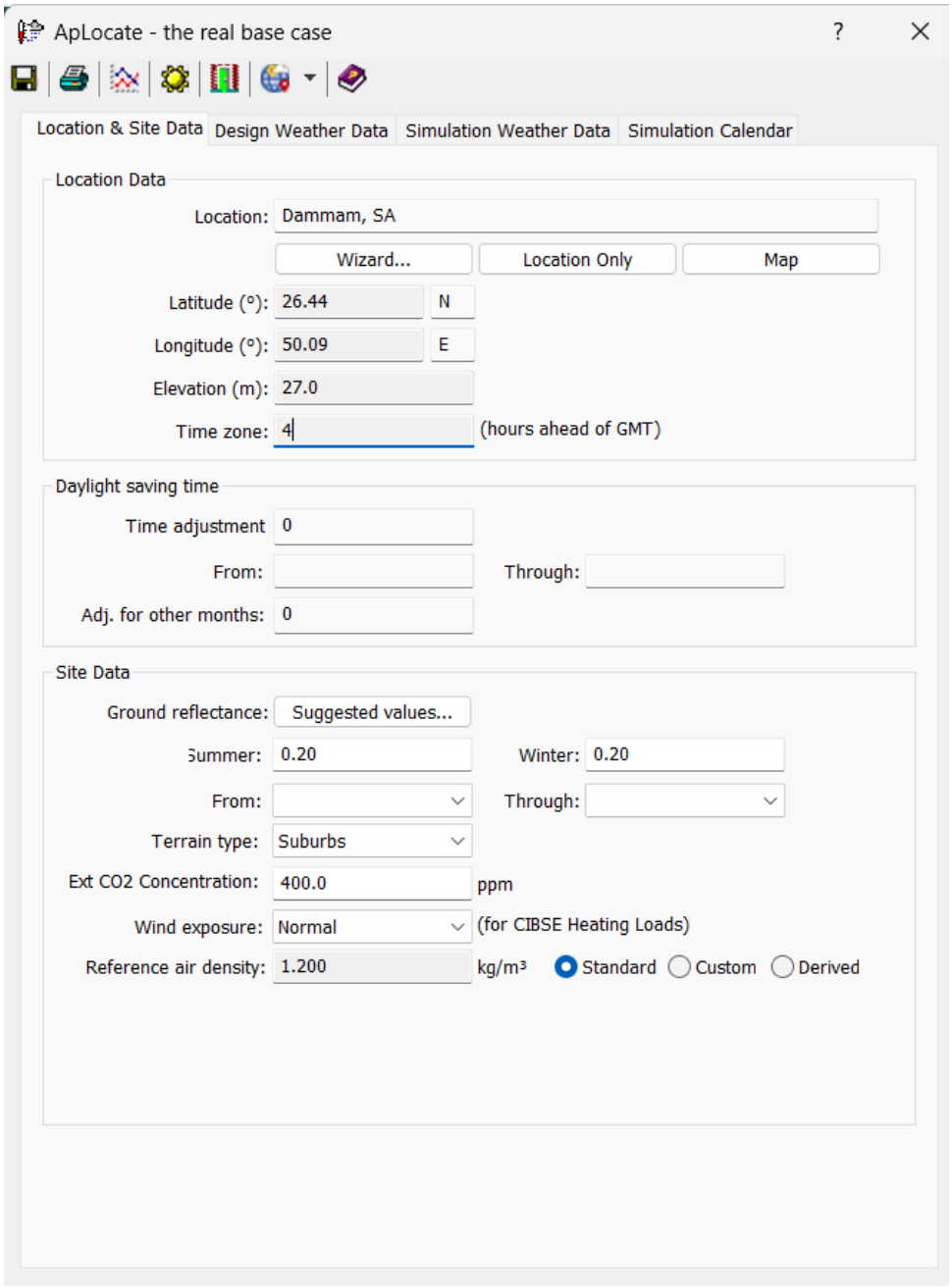


Figure A9. The Base case IES model location which was obtain from the APlocate feature.

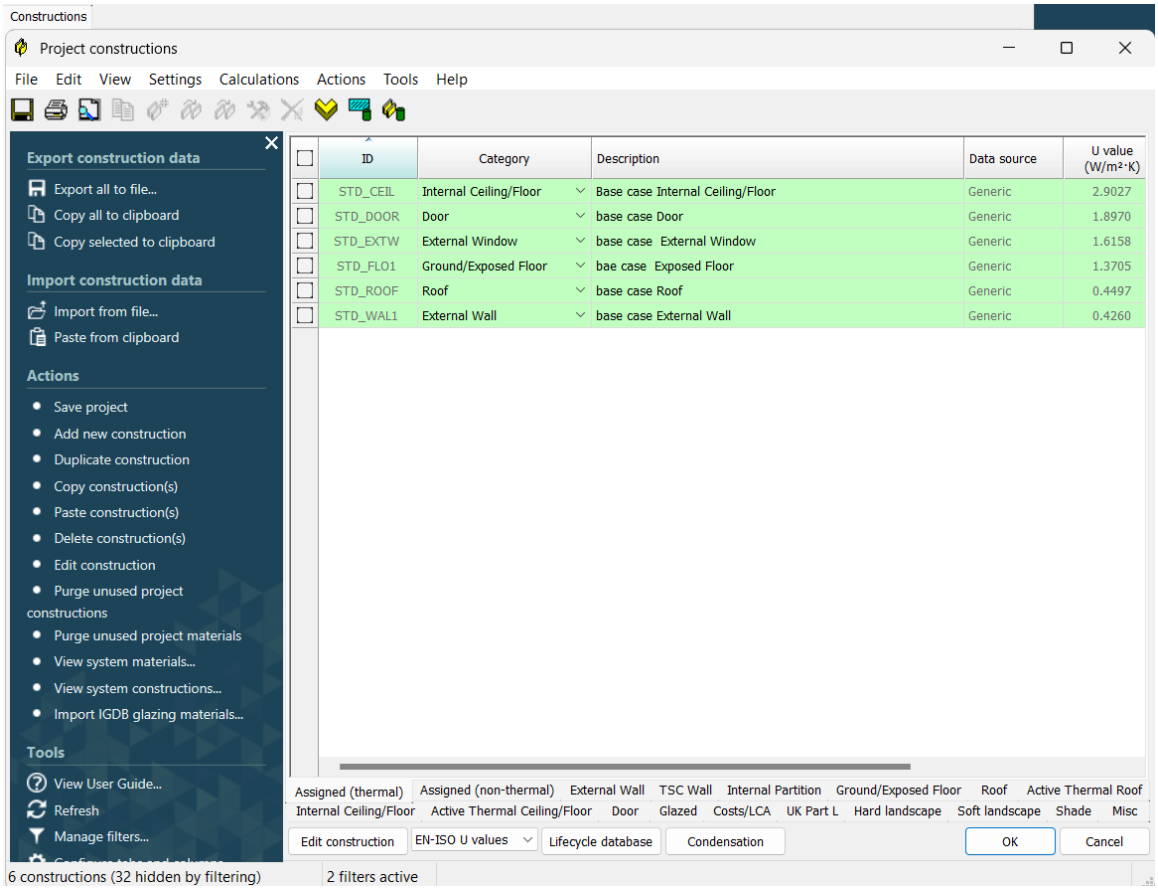


Figure A10. The Base case IES project construction envelope U-value.

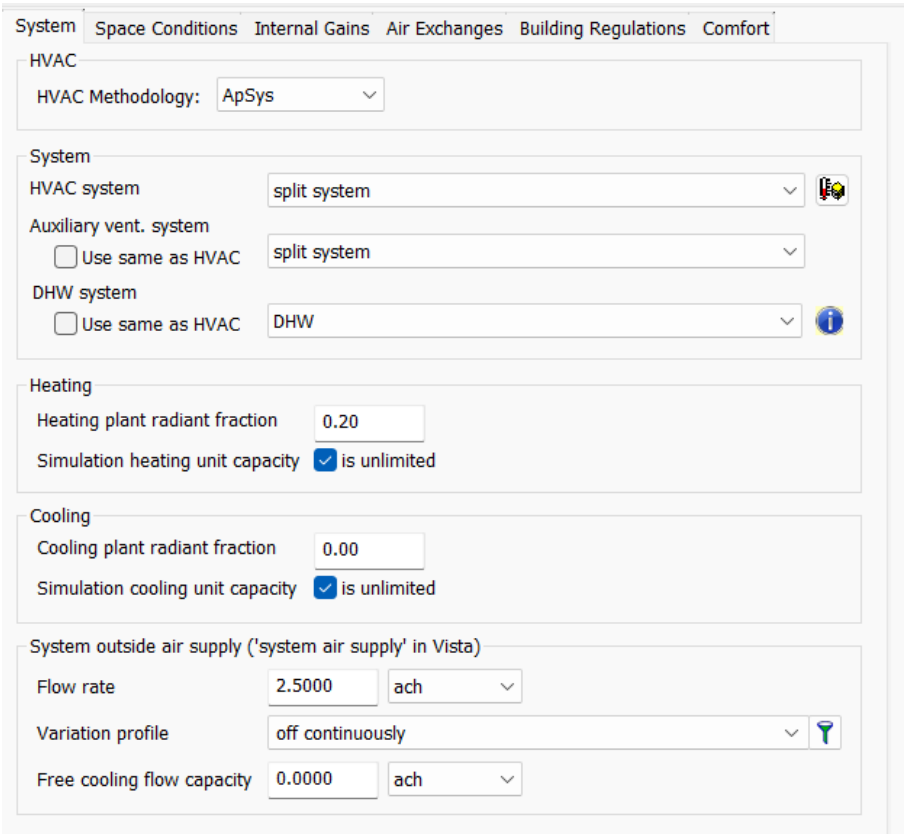


Figure A11. The Base case IES thermal specification.

Appendix E: Actual Architecture Plans and Electricity Bills For the selected home.

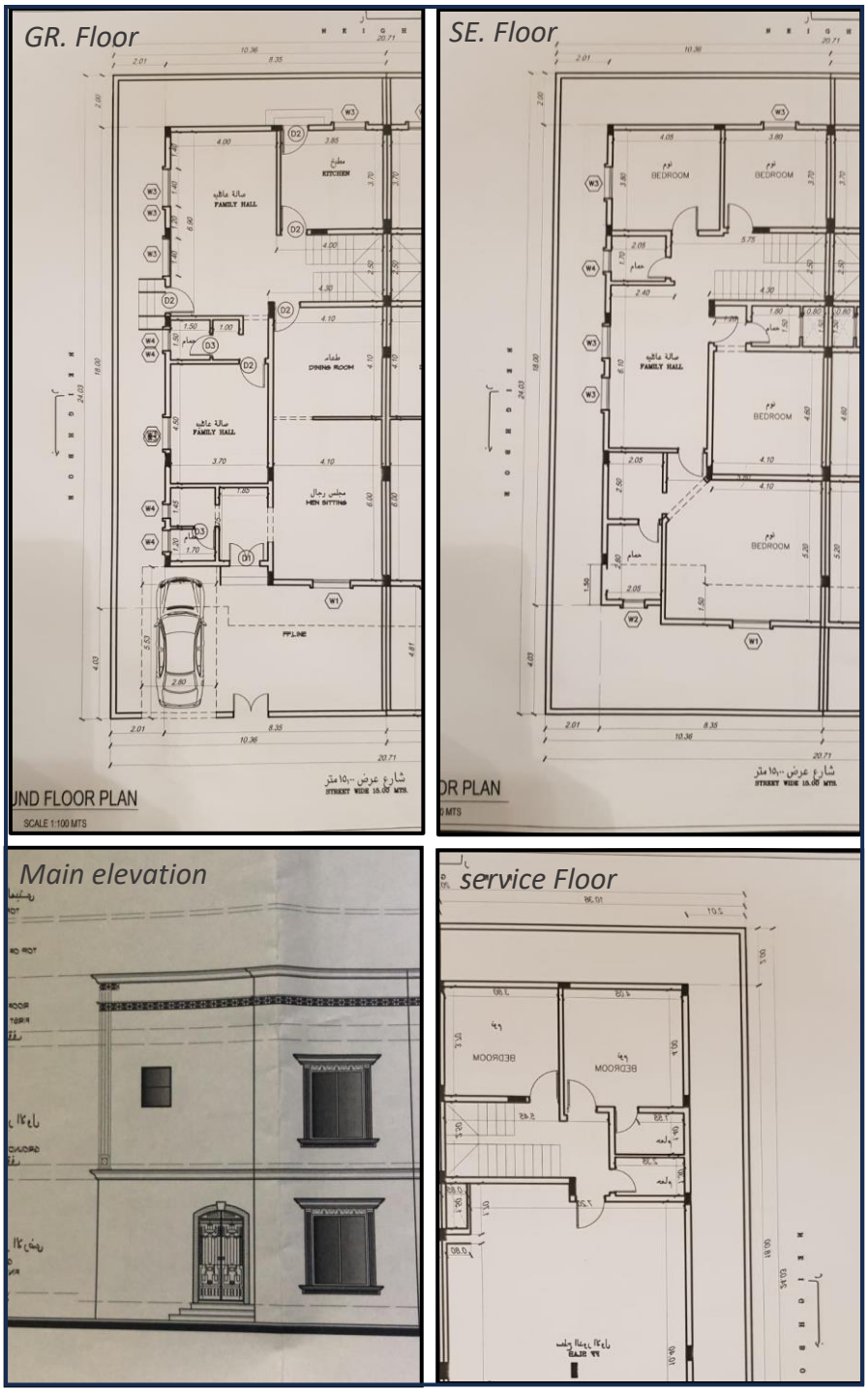


Figure A12. Architecture Plans (Ground Floor, First Floor, North Elevation).

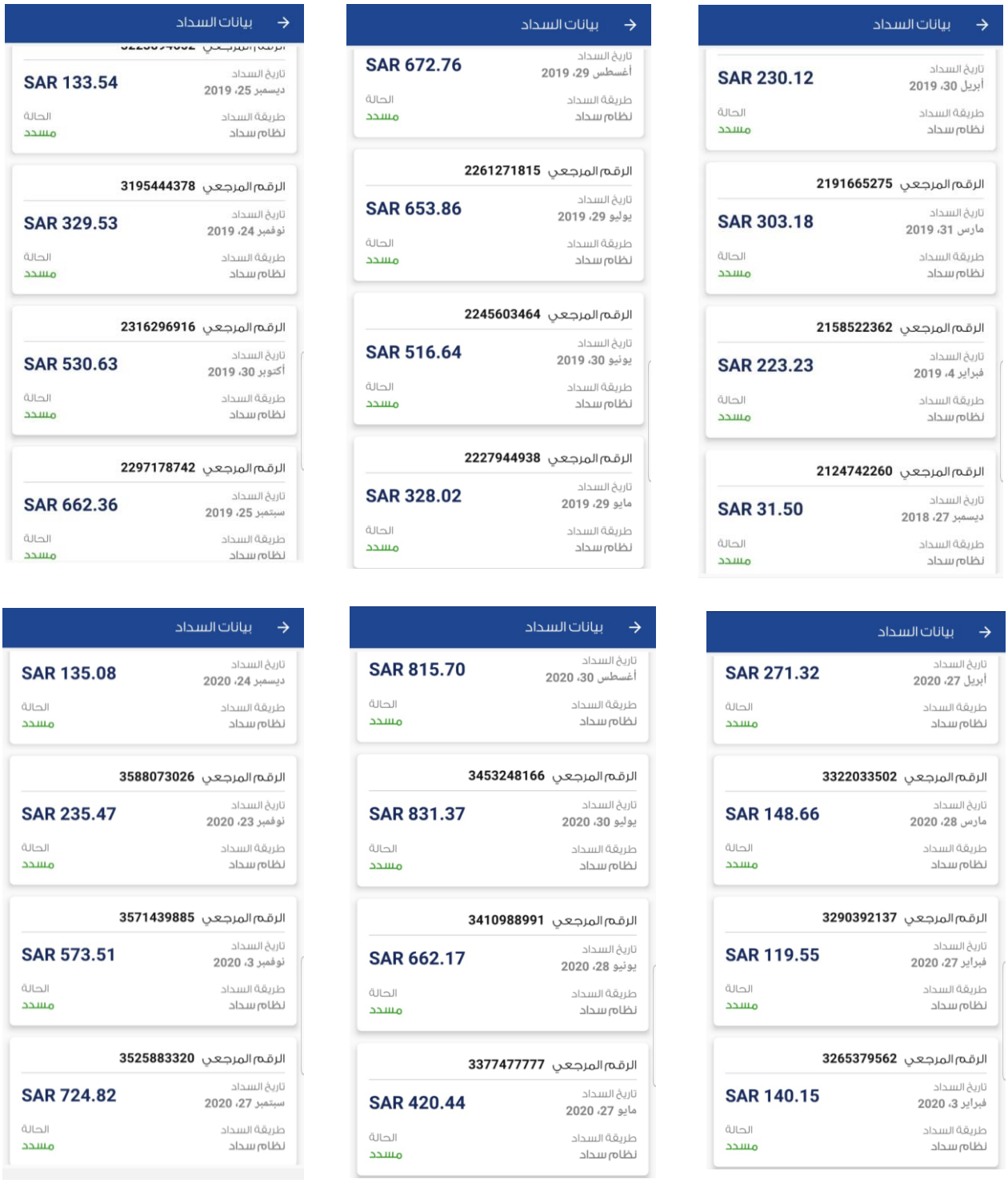


Figure A13. Electricity Bills from (27th December 2018 to 24th December 2020).

Appendix F: Daylighting Building template manager input for the dimming profiles.

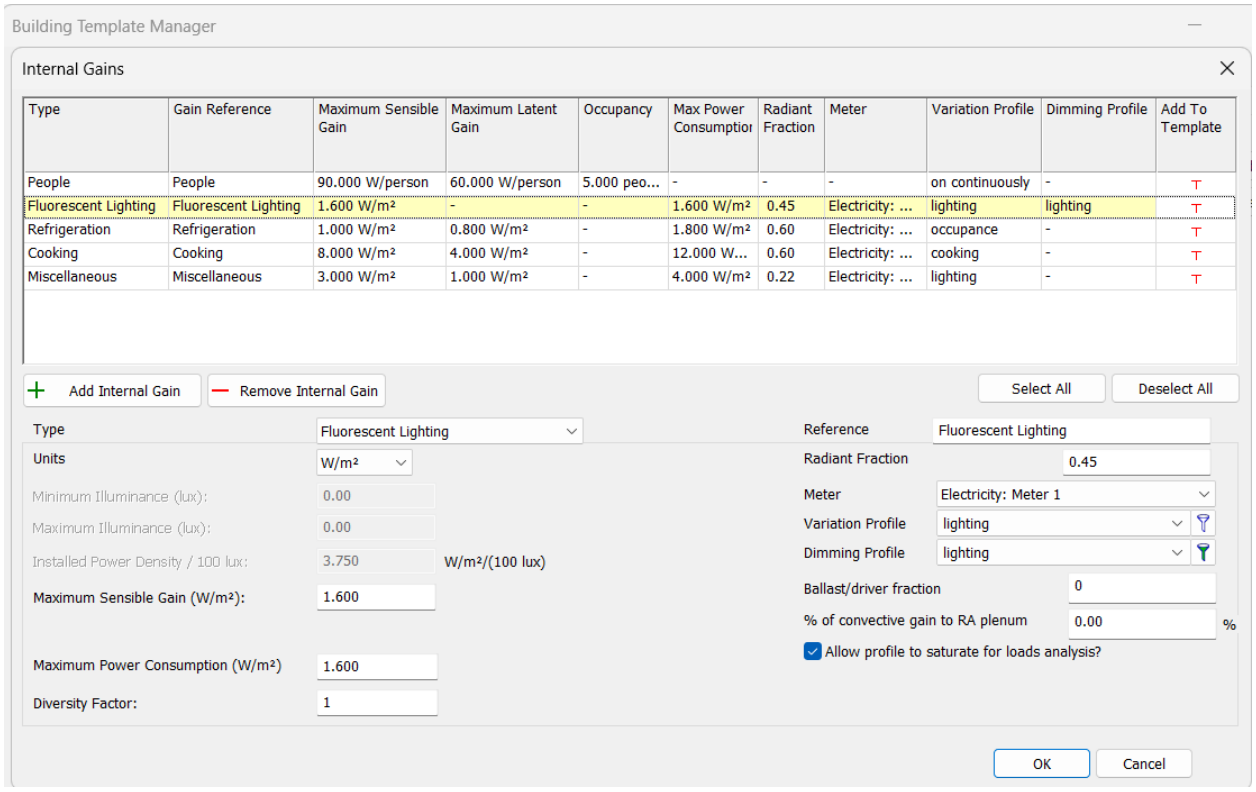


Figure A14. Building template manager showing lighting dimming profile.

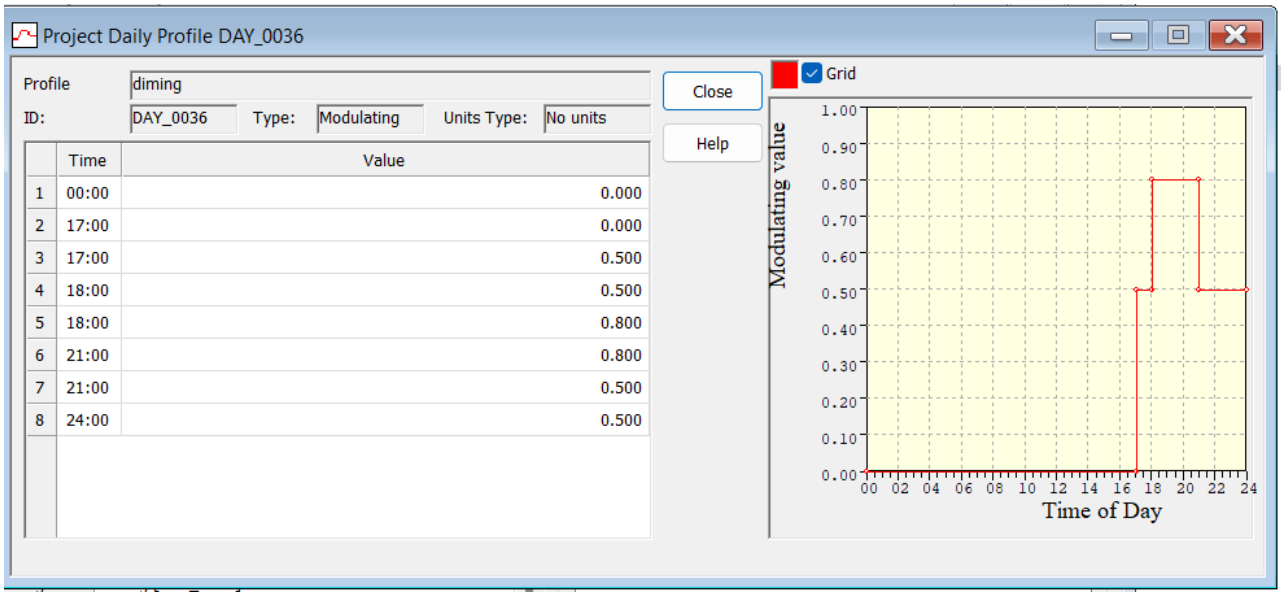


Figure A15. Building template manager showing lighting dimming daily profile.

Appendix G: author's conceptualisation of an integrated community of NZEHs built-in the region.



Figure A16. Imaginary perspective for how the NZEH prototype will be in the region.