Improving The Energy Efficiency of Existing Residential Buildings in Benghazi, Libya, to Meet the Net Zero Energy Buildings Target by A Hybrid Retrofit Approach

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Abstract

Energy use in residential buildings in Libya is found to constitute the largest percentage of energy demand and carbon dioxide emissions as compared with other sectors. Since a large percentage of the total number of existing buildings is expected to remain in use in the future, there is therefore a need to reduce these buildings' energy use through thermal refurbishment and retrofitting, which will have a substantial impact on reducing carbon emissions. Although some previous studies have considered the development of energy-efficient residential buildings for Libya, little attention has been paid to retrofitting existing housing stock. In addition, although integration of renewable energy systems into buildings has the potential to significantly lower greenhouse gas emissions, few attempts have been made to investigate the potential for meeting buildings' energy needs with renewable energy. This study aims to fill this gap in the current literature by identifying optimal solutions for retrofitting existing residential building stock in Libya to meet net zero energy buildings targets, by proposing a hybrid retrofit approach.

Empirical and numerical research techniques are adopted to achieve the aim of this study. Three different housing types located in Benghazi in Libya: terraced houses, detached houses, and apartment buildings; were surveyed and monitored to collect information about these buildings, and to assess their energy and thermal performance. Based on the collected data, the three case study buildings were modelled in DesignBuilder software. To ensure that the simulated building models closely matched the real building, the building models were calibrated according to ASHRAE Guideline 14-2002 calibration criteria, using both actual energy consumption and indoor zone temperatures. Results from the building monitoring study show that the three case study buildings consume the most energy for cooling in the summer, and for heating in the winter. The base case simulation results reveal that heat gain and loss through the building envelope, including roof, walls, and windows, are the main contributors to cooling and heating energy consumption. Therefore, to improve the energy performance of the case study buildings, passive retrofit measures are employed. These include upgrading the roof and walls with low-impact biobased insulation materials, in addition to employing other retrofit measures, including adding shading, and window glazing replacement.

Each single retrofit measure was first assessed individually in terms of its influence on energy reduction. Then, combinations of these measures were assessed via a multi-objective optimisation method, to find the optimal solutions to achieve a trade-off between energy reduction and thermal comfort. Further investigations were conducted to investigate the potential for meeting the target of net zero energy buildings by integrating renewable energy systems. The findings reveal that, for a two-storey terraced house (Case Study 1), roof insulation is the most effective solution, achieving a reduction in respective cooling and heating energy consumption of up to 25.7% and 43.2% without

compromising the percentage of comfort hours. For detached houses (Case Study 2), it is found that installing wall insulation is the most effective solution. This contributes to a reduction in cooling and heating energy of up to 44.84% and 29.15%, respectively, without compromising the percentage of comfort hours. Upgrading the external walls with insulation materials also optimises energy performance for apartment buildings (Case Study 3), in which considerable reductions, of 40.8% and 71% respectively in cooling and heating energy, are achieved without compromising the percentage of comfort hours. A set of trade-off solutions result from the multi-objective optimisation method. However, the optimal retrofit combination for energy reduction includes upgrading the roof and external walls with insulation materials at a U-value of 0.1 W/m^2k, a glazing system with triple or double Low-E glazing, and window shading at 0.5 projection depth, with this combination showing an acceptable range of discomfort hours. In addition, reductions in energy consumption of up to 53.27%, 60.5 % and 64.41% are shown in case studies 1, 2, and 3, respectively. The combination of these measures helps in meeting or nearly meeting the Passivhaus retrofit target of 135 $kWh/m^2/y$ for primary energy demand, and 30 $kWh/m^2/y$ for primary cooling and heating energy demand. Moreover, integrating a photovoltaic system of 400W on the roof helps in meeting remaining energy needs and achieving the target of net zero energy buildings for all case study buildings.

Keywords: Residential building retrofit, building monitoring, building energy modelling (BEM), DesignBuilder, model calibration, optimisation simulation, hybrid retrofit approach, multi-objective optimisation, energy retrofit measures (ERMs), Passivhaus, NZEBs.

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Table of Contents

Chapter 1: Introduction......1

1.1 Research Background......1

1.2 Importance of the Research......2

1.3 Research Gap......3

1.4 Statement of the Research Problem......3

1.5 Research Questions......4

1.6 Aim and objectives......4

1.7 Research Scope and Focus......5

1.8 Research Structure and Framework......6

1.9 Chapter Summary......7

Chapter 2: Overview of The Study Context (Benghazi, Libya)......9

2.1 Introduction......9

2.2 Location and Climatic Parameters of Benghazi City......9

2.3 Energy Consumption of Residential Buildings in Libya......11

2.4 Libyan Building Energy Efficiency Codes, Legislation, and Regulations......14

2.5 Solar Energy Potential in Libya......15

2.6 Residential Building Industry in Libya......16

2.7 Vernacular and Contemporary Dwellings in Libya......18

2.7.1 Socio-Cultural Factors......18

2.7.2 Environmental Factors......19

2.8 Contemporary Libyan Housing......20

2.8.1 Contemporary Housing Typology in Benghazi......23

2.9 Chapter summary......27

Chapter 3: Literature Review......28

3.1 Introduction......28

3.2 Theoretical Background......28

3.2.1 Energy Retrofit Measures for Existing Residential Buildings in Hot Climates......28

3.2.2 Thermal comfort......40

3.2.3 Energy efficient building standards (Passivhaus standard)......42

3.3 A Systematic literature review......43

3.3.1 Objectives of the literature review......43

3.3.2 Materials and Methods......44

3.3.3 Results......49

3. 4 Chapter Summary......66

Chapter 4: Research Methodology 68

4.1 Introduction 68

4.2 Research Methodology 68

4.2.1 Case Study Selection 71

4.2.2 Building Survey and Monitoring 79

4.2.3 Building Energy Modelling and Simulation 93

4.2.4 Case Study Model Optimisation 101

4.3 Data analysis 107

4.4 Chapter Summary 108

Chapter 5: Buildings Monitoring Study - Results and Discussion 109

5.1 Introduction 109

5.2 Case Study 1 109

5.2.1 Indoor Thermal Conditions 109

5.2.2 Energy Consumption 115

5.3 Case Study 2 117

5.3.1 Indoor Thermal Conditions 117

5.3.2 Energy Consumption 120

5.4 Case Study 3 122

5.4.1 Indoor Thermal Conditions 122

5.4.2 Energy Consumption 125

5.5 Discussion of Building Monitoring Study Results 127

5.6 Chapter Summary 129

Chapter 6: Building Calibration Simulation - Results and Discussion 130

6.1 Introduction 130

6.2 Calibration Results for Case Study Building 1 130

6.2.1 Setting Up the Sensitivity Analysis 130

6.2.2 Monthly Energy Consumption Calibration 133

6.2.3 Hourly Energy Consumption Calibration 134

6.2.4 Monthly Zone Temperature Calibration 136

6.2.5 Hourly Zone Temperature Calibration 137

6.3 Calibration Results for Case Study Building 2 139

6.3.1 Setting Up the Sensitivity Analysis 139

6.3.2 Monthly Energy Consumption Calibration 141

6.3.3 Hourly Energy Consumption Calibration 142

6.3.4 Monthly Zone Temperature Calibration 144

6.3.5 Hourly Zone Temperature Calibration **144**
6.4 Calibration Results for Case Study Building 3 145
6.4.1 Setting Up the Sensitivity Analysis **145**
6.4.2 Monthly Energy Consumption Calibration **148**
6.4.3 Hourly energy consumption calibration **149**
6.4.4 Monthly zone temperature calibration **150**
6.4.5 Hourly zone temperature calibration **151**
6.5 Chapter Summary 151
Chapter 7: Building Simulation and Optimisation Study - Results and Discussion 153
7.1 Introduction 153
7.2 Base Case Simulation Results 153
7.2.1 Annual Energy Consumption Simulation Results **153**
7.2.2 Heat Balance Simulation Results **155**
7.3 Case Study Model Optimisation Result 158
7.3.1 Case Study 1- Optimisation Results **159**
7.3.2 Case Study 2- Optimisation Results **176**
7.3.3 Case Study 3- Optimisation Results **191**
7.4 Final Discussion 208
7.5 Chapter Summary 211
Chapter 8: Conclusion and Recommendations For Future Work 212
8.1 Introduction 212
8.2 Research Summary 212
8.3 Research Contributions to The Body of Knowledge 215
8.3.1 Theoretical Contributions **216**
8.3.2 Policy Level and Practical Contributions **216**
8.3.3 Environmental and Economic Contributions **217**
8.3.4 Social Contributions **217**
8.4 Research Limitations 217
8.5 Suggested Areas for Future Research 218
Publications From This Research 219
References 220
Appendices 238

List of Figures

Figure 1. 1 Global CO_2 emission by sector (Abergel et al. 2017) ... 1
Figure 1. 2 Research structure ... 8

Figure 2. 1World map showing the Köppen-Geiger climate classification for Libya (Kottek et al. 2006) ... 10
Figure 2. 2 Monthly average dry bulb temperature, Benghazi, Libya (Meteoblue 2021) ... 11
Figure 2. 3 Average monthly relative humidity, Benghazi, Libya (Weatheratlas 2021) ... 11
Figure 2. 4 World energy consumption per capita, 2013 (WorldBank 2013) ... 12
Figure 2. 5 Electricity generation in Libya, 2000 to 2010 (GECOL 2012) ... 13
Figure 2. 6 Electricity consumption by sector in Libya (Tawil et al. 2018) ... 13
Figure 2. 7 Global horizontal irradiation map of Libya (The World Bank Group 2019) ... 15
Figure 2. 8 Courtyard house within the compact fabric of the old city of Tripoli (Eltrapolsi et al. 2022) ... 20
Figure 2. 9 Spatial development of Benghazi (UPA 2009) ... 21
Figure 2. 10 The Benghazi Metropolitan area: existing land use (UPA 2009) ... 22
Figure 2. 11 Compact form of grid pattern and altered courtyard buildings (UPA 2009; Mohamed 2013) ... 24
Figure 2. 12 Design layout of villa type (UPA 2009; Mohamed 2013) ... 25
Figure 2. 13 Design layout of apartment type (UPA 2009; Mohamed 2013) ... 27

Figure 3. 1 Demonstration of how combining energy efficiency and renewable energy strategies reduces the need for conventional energy (Hayter and Kandt 2011) ... 29
Figure 3. 2 The effect of thermal mass in summer and winter (ACarchitects 2019) ... 30
Figure 3. 3 Primary energy consumption versus WWR (Marino et al. 2017) ... 35
Figure 3. 4 Influential factors for occupant behaviour (Tam et al. 2018) ... 38
Figure 3. 5 Relationship of PMV to PPD (ASHRAE55 2017) ... 41
Figure 3. 6 Acceptable operative temperature ranges for naturally conditioned spaces (ASHRAE55 2017) ... 42
Figure 3. 7 The locations of Libya and neighbouring Mediterranean countries included in this review. Adopted from (WikimediaCommons 2024) ... 44
Figure 3. 8 Main categories of building retrofit measures adopted from (Ma et al. 2012) ... 46
Figure 3. 9 Flow chart for the literature selection criteria ... 50
Figure 3. 10 Number of articles per reference type ... 52
Figure 3. 11 Number of studies by country ... 52
Figure 3. 12 Number of studies by year of publication ... 52
Figure 3. 13 Use of various retrofit measures in previous research ... 61

Figure 4. 1 Outline of the research approach ... 70
Figure 4. 2 Case study building locations ... 72
Figure 4. 3 Terraced house location ... 73
Figure 4. 4 Terraced house form and site layout ... 73
Figure 4. 5 Terraced house design layout ... 74
Figure 4. 6 Detached house location ... 74
Figure 4. 7 Detached house form and site layout ... 75

Figure 4. 8 Detached house design layout 75
Figure 4. 9 Apartment building location 76
Figure 4. 10 Apartment building form and site layout........ 76
Figure 4. 11 Flat design plan 77
Figure 4. 12 Weather station location and installation on the building roof 86
Figure 4. 13 Plan shows the indoor sensor locations on both the ground and first floor of Case Study 1 87
Figure 4. 14 Plan shows indoor sensor locations in Case Study 2 88
Figure 4. 15 Plan showing indoor sensor locations in Case Study 3 89
Figure 4. 16 Heat flux sensor installation on both the limestone block wall and hollow concrete block wall........ 90
Figure 4. 17 Energy meter location and installation on the ground floor - Case Study 1........ 91
Figure 4. 18 Energy meter location and installation on the first floor - Case Study 1........ 91
Figure 4. 19 Energy meter locations and installation for Case Study 2 92
Figure 4. 20 Energy meter locations and installation for Case Study 3 93
Figure 4. 21 Simulation plan (Author 2022)........ 94
Figure 4. 22 Calibration plan (Author 2022) 98
Figure 4. 23 A typical schematic flow diagram for building model calibration using sensitivity analysis (Li et al. 2016) 100
Figure 4. 24 optimisation simulation plan 101
Figure 4. 25 The thermal conductivity of camel hair, measured by ISOMET 2114........ 103

Figure 5. 1 Comparison of the maximum, mean, and minimum indoor temperature values between ground floor and first floor spaces (summer)........ 110
Figure 5. 2 Comparison of the maximum, mean, and minimum indoor temperature values between ground floor and first floor spaces (winter)........ 111
Figure 5. 3 Comparison of the maximum, mean, and minimum indoor temperature values between ground floor and first floor spaces (transition month)........ 112
Figure 5. 4 The maximum, mean, and minimum indoor temperature values of ground-floor spaces when air conditioner is ON and OFF 113
Figure 5. 5 The maximum, mean, and minimum indoor temperature values of first-floor spaces when air conditioner is ON and OFF 114
Figure 5. 6 Monthly energy consumption from 8th June 2022 to 7th June 2023........ 116
Figure 5. 7 Breakdown of energy consumption of Case Study 1- Summer 116
Figure 5. 8 Breakdown of energy consumption of Case Study 1- Winter........ 116
Figure 5. 9 The maximum, mean, and minimum indoor temperature values of different spaces in summer month- Case Study 2........ 117
Figure 5. 10 The maximum, mean, and minimum indoor temperature values of different spaces in a winter month- Case Study 2 118
Figure 5. 11 The maximum, mean, and minimum indoor temperature values of different spaces in a transition month- Case Study 2 119
Figure 5. 12 The maximum, mean, and minimum indoor temperature values when air conditioner is ON and OFF 120
Figure 5. 13 Monthly energy consumption from 7th July 2022 to 6th July 2023 121
Figure 5. 14 Breakdown of energy consumption of Case Study 2- Summer 121
Figure 5. 15 Breakdown of energy consumption of Case Study 2- Winter........ 121

Figure 5. 16 The maximum, mean, and minimum indoor temperature values of different spaces in a summer month- Case Study 3 123
Figure 5. 17 The maximum, mean, and minimum indoor temperature values of different spaces in a winter month- Case Study 3 123
Figure 5. 18 The maximum, mean, and minimum indoor temperature values of different spaces in transition month- Case Study 3 124
Figure 5. 19 The maximum, mean, and minimum indoor temperature values when air conditioners are ON and OFF 125
Figure 5. 20 Monthly energy consumption from 7th August 2022 to 6th August 2023 126
Figure 5. 21 Breakdown of energy consumption of Case Study 3- Summer 126
Figure 5. 22 Breakdown of energy consumption of Case Study 3- Winter 127

Figure 6. 1 Case Study Building 1 modelling in DesignBuilder. 130
Figure 6. 2 Cooling load sensitivity analysis results - Case Study 1 133
Figure 6. 3 Heating load sensitivity analysis results - Case Study 1 133
Figure 6. 4 Monthly energy consumption calibration results for Case Study 1 134
Figure 6. 5 General trend in simulated versus monitored energy use data between 19th and 22nd June 2022 135
Figure 6. 6 Air temperature of the ground floor lounge against AC energy use. 135
Figure 6. 7 Running average of measured and simulated building energy consumption in one summer month, between 8th of June 2022 and 6th of July 2022. 136
Figure 6. 8 Running average of measured and simulated building energy consumption in one winter month, between 12th December 2022 and 10th January 2023. 136
Figure 6. 9 Monthly zone temperature calibration of ground floor spaces- Case Study 1. 137
Figure 6. 10 Monthly zone temperature calibration of first floor spaces- Case Study 1. 137
Figure 6. 11 Hourly zone temperature calibration of ground floor spaces - Case Study 1 138
Figure 6. 12 Hourly zone temperature calibration of first floor spaces - Case Study 1 138
Figure 6. 13 Case Study building 2 modelling in DesignBuilder. 139
Figure 6. 14 Cooling load sensitivity analysis result - Case Study 2 141
Figure 6. 15 Heating load sensitivity analysis result- Case Study 2 141
Figure 6. 16 Monthly calibration results for Case Study 2 142
Figure 6. 17 General trend simulated versus monitored energy use data between 11th and 13th July 2022. 142
Figure 6. 18 Running average of measured and simulated building energy consumption in one summer month between 9th July 2022 and 5th August 2022. 143
Figure 6. 19 Running average of monitored and simulated building energy consumption in one winter month between 24th January 2023 and 21st February 2023. 143
Figure 6. 20 Monthly zone temperature calibration - Case Study 2. 144
Figure 6. 21 Hourly zone temperature calibration - case study 2 145
Figure 6. 22 Case study building 3 modelling in DesignBuilder. 145
Figure 6. 23 Cooling load sensitivity analysis result - Case Study 3. 147
Figure 6. 24 Heating load sensitivity analysis result - Case Study 3 148
Figure 6. 25 Shoebox energy model to estimate the whole building's energy consumption. 148
Figure 6. 26 Monthly calibration results for Case Study 3. 149
Figure 6. 27 Running average of measured and simulated building energy consumption in one summer month between 11th August 2022 and 7th September 2022. 149

Figure 6. 28 Running average of measured and simulated building energy consumption in one winter month between 15th January 2023 and 15th February 2023 150
Figure 6. 29 Monthly zone temperature calibration of indoor spaces - case study 3. 150
Figure 6. 30 Hourly zone temperature calibration for ground floor spaces. 151

Figure 7. 1 Energy end uses - Case Study 1 154
Figure 7. 2 Energy end uses - Case Study 2 154
Figure 7. 3 Energy end uses - Case Study 3 155
Figure 7. 4 Heat balance report for summer - Case Study 1. 156
Figure 7. 5 Heat balance report for winter- Case Study 1. 156
Figure 7. 6 Heat balance report for summer - Case Study 2. 157
Figure 7. 7 Heat balance report for winter - Case Study 2. 157
Figure 7. 8 Heat balance report for summer - Case Study 3. 158
Figure 7. 9 Heat balance report for winter - Case Study 3. 158
Figure 7. 10 Influence of roof insulation on cooling and heating energy consumption 160
Figure 7. 11 Influence of roof insulation on the percentage of comfort hours during summer and winter 161
Figure 7. 12 Influence of roof insulation on indoor temperature in summer and winter 161
Figure 7. 13 Influence of wall insulation on cooling and heating energy consumption 163
Figure 7. 14 wall insulation influence on the comfort hours during summer and winter 164
Figure 7. 15 The influence of external wall insulation on indoor temperature in summer and winter 164
Figure 7. 16 Influence of ground floor insulation on cooling and heating energy consumption 165
Figure 7. 17 Influence of ground floor insulation on comfort hours during summer and winter 166
Figure 7. 18 Influence of ground floor insulation on indoor temperature in summer and winter 166
Figure 7. 19 Influence of window glazing type and framing system on cooling and heating energy consumption 168
Figure 7. 20 Window glazing type and frame vs. the percentage of comfort hours in summer and winter 168
Figure 7. 21 Influence of window glazing type on indoor temperature in the summer and winter 168
Figure 7. 22 Solar shading devices' influence on cooling and heating energy consumption 169
Figure 7. 23 Solar shading devices' influence on the percentage of comfort hours in summer and winter 170
Figure 7. 24 Influence of window shading on indoor temperature in summer and winter 170
Figure 7. 25 Multi - objective optimisation results 1,- Case Study 1. 172
Figure 7. 26 Multi - objective optimisation results 2, Case study 1. 173
Figure 7. 27 Influence of the optimal retrofit solution on indoor temperature in summer and winter 174
Figure 7. 28 Photovoltaic panel arrangement- Case Study 1 175
Figure 7. 29 The effect of roof insulation on cooling and heating energy consumption 177
Figure 7. 30 Influence of roof insulation on the percentage of comfort hours during summer and winter 178
Figure 7. 31 Influence of roof insulation on indoor temperature in summer and winter 178
Figure 7. 32 Influence of external wall insulation on cooling and heating energy consumption 179
Figure 7. 33 Influence of external wall insulation on the percentage of comfort hours during summer and winter 180

Figure 7. 34 The influence of external wall insulation on indoor temperature in summer and winter 180
Figure 7. 35 Influence of ground floor insulation on cooling and heating energy 181
Figure 7. 36 Influence of ground floor insulation on the percentage of comfort hours during summer and 182
Figure 7. 37 Influence of ground floor insulation on indoor temperature in the summer and winter 182
Figure 7. 38 Influence of window glazing type and framing system on cooling and heating energy consumption 183
Figure 7. 39 Influence of window glazing type and framing system on the percentage of comfort hours during summer and winter 184
Figure 7. 40 Influence of window glazing type on indoor temperature in summer and winter 184
Figure 7. 41 Influence of local shading devices on cooling and heating energy consumption 185
Figure 7. 42 Influence of window shading on the percentage of comfort hours during summer and winter 186
Figure 7. 43 Influence of solar shading devices on the percentage of comfort hours in summer and winter 186
Figure 7. 44 Multi-objective optimisation result 1,- Case Study 2.. 187
Figure 7. 45 Multi-objective optimisation result 2, Case Study 2. 188
Figure 7. 46 Influence of the optimal retrofit solution on indoor temperature in summer and winter 189
Figure 7. 47 Photovoltaic panel arrangement- Case Study 2.. 190
Figure 7. 48 Influence of roof insulation on cooling and heating energy consumption..................... 192
Figure 7. 49 Influence of roof insulation on the percentage of comfort hours during summer and winter 193
Figure 7. 50 Influence of roof insulation on indoor temperature in summer and winter.................. 193
Figure 7. 51 Influence of wall insulation on cooling and heating energy consumption..................... 194
Figure 7. 52 Influence of wall insulation on comfort hours during summer and winter.................... 195
Figure 7. 53 Influence of external wall insulation on indoor temperature in the summer and winter 196
Figure 7. 54 Influence of ground floor insulation on cooling and heating energy 197
Figure 7. 55 Influence of ground floor insulation on comfort hours during summer and winter...... 197
Figure 7. 56 Influence of ground floor insulation on indoor temperature in summer and winter 198
Figure 7. 57 Influence of window glazing type and framing system on cooling and heating energy. 199
Figure 7. 58 Influence of window glazing type and framing system on the percentage of comfort hours during summer and winter 200
Figure 7. 59 The influence of window glazing type on indoor temperature in summer and winter.. 200
Figure 7. 60 The influence of window shading on cooling and heating energy................................ 201
Figure 7. 61 Solar shading devices' influence on the percentage of comfort hours in summer and winter 201
Figure 7. 62 Solar shading devices' influence on the percentage of comfort hours in summer and winter 202
Figure 7. 63 Multi-objective optimisation result 1, Case Study 3. 203
Figure 7. 64 multi-objective optimisation result 2, Case Study 3. 204
Figure 7. 65 The influence of the optimal retrofit solution on indoor temperature in summer and winter 205
Figure 7. 66 Photovoltaic panel arrangement- Case Study 3.. 207

List of Tables

Table 2. 1 Energy consumption per capita for different MENA countries (Al Shamsi 2017)................12
Table 2. 2 Status of building energy regulation in MENA countries (Al Shamsi 2017) 14
Table 2. 3 Construction materials used in existing residential buildings in Libya (Gabril 2014; Ali 2018) . 17
Table 2. 4 Housing stock in the Benghazi Metropolis – 2006 (UPA 2009) 23

Table 3. 1 Automated and manual solar shading control strategy (Yao 2014) 36
Table 3. 2 Calibration criteria of the Federal Energy Management Program (FEMP), ASHRAE Guideline 14 and International Performance Measurement and Verification Protocol (IPMVP) (Fernandez Bandera and Ramos Ruiz 2017). 48
Table 3. 3 The obtained literature for this systematic review, and the themes identified to analyses the literature. 52

Table 4. 1 Case Study buildings information..77
Table 4. 2 Construction materials of the case study buildings 78
Table 4. 3 Indoor thermal condition monitoring plan 80
Table 4. 4 EnviroTrack Weather Station & Data Logger - USB Data Communication (Tempcon Instrumentation, West Sussex, UK) 81
Table 4. 5 Solar radiation detector PCE-SPM 1 (PCE Instruments UK Ltd., Manchester, UK) 82
Table 4. 6 Tempo Disc™ 4 in 1 Bluetooth Sensor Logger (Blue Maestro, USA) 83
Table 4. 7 U-value and heat flux sensor specifications (GreenTEG, Switzerland) 83
Table 4. 8 Tiny-Tag View 2 Current Logger (Gemini Data Loggers, UK)...85
Table 4. 9 Socket energy meter (RS, UK) 85
Table 4. 10 Summary of main simulation settings..95
Table 4. 11 Calibration criteria, ASHRAE Guideline 14-2002 99
Table 4. 12 The thermal properties of biobased insulation materials used for materials setup in DesignBuilder 103
Table 4. 13 Specifications for biobased insulation materials used to optimise the roof and walls ...103
Table 4. 14 The thickness of each biobased insulation material to meet the optimised U-values (DesignBuilder library) 104
Table 4. 15 Glazing type used for window optimisation (DesignBuilder library) 105
Table 4. 16 Shading optimisation parameters 106

Table 6. 1 Selected parameters for sensitivity analysis- case study 1 131
Table 6. 2 Selected parameters for sensitivity analysis - case study 2. 139
Table 6. 3 Selected parameters for sensitivity analysis - case study 3. 146

Table 7. 1 Design parameters options for multi objective optimisation 171
Table 7. 2 The optimal retrofit solutions and number of solar panels needed to meet NZEBs- Case Study1 176
Table 7. 3 The optimal retrofit solutions and number of solar panels needed to meet NZEBs- Case Study 2 191
Table 7. 4 The optimal retrofit solutions and number of solar panels needed to meet NZEBs- Case Study 3 207

List of Acronyms

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BEM	Building Energy Modelling
COP	Coefficient of performance
CV(RMSE)	Coefficient of variation of the root mean squared error
DHW	Domestic hot water
ERMs	Energy retrofit measures
EThOS	The Electronic Theses Online Service
GECOL	General Electricity Company of Libya
HVAC	Heating, Ventilation and Air Conditioning
MOOP	Multi-objective optimisation problem
NMBE	Normalised mean bias error
NZEBs	Net Zero Energy Buildings
PRISMA	The preferred reporting items for systematic reviews and meta-analyses
PV	Solar photovoltaic system
SOOP	Single-objective optimisation problem
SRC	Standardised regression coefficient
UPA	The Urban Planning Agency of Benghazi, Libya
WWR	WWR window-to- wall ratio

Chapter 1: Introduction

1.1 Research Background

The problem of global warming is likely to make existing buildings increasingly thermally uncomfortable and, as a result, their cooling and heating loads can be expected to increase in the future. According to Abergel et al. 2017, over 35% of global energy consumption and 40% of energy-related CO_2 emissions are attributed to the building and construction industries (Figure1.1). Moreover, energy use in residential buildings is found to constitute the largest percentage of energy demand and carbon dioxide emission (Nejat et al. 2015). As a result, this sector has a great potential for long-term energy savings and reductions in greenhouse gas emissions. In addition, since new buildings account for only a small percentage of the national building stock (Ruparathna et al. 2016), with 80% of the total number of existing buildings expected to remain in the future (Xing et al. 2011; Bienert et al. 2023), there is a need to reduce their energy use through thermal refurbishment and retrofitting.

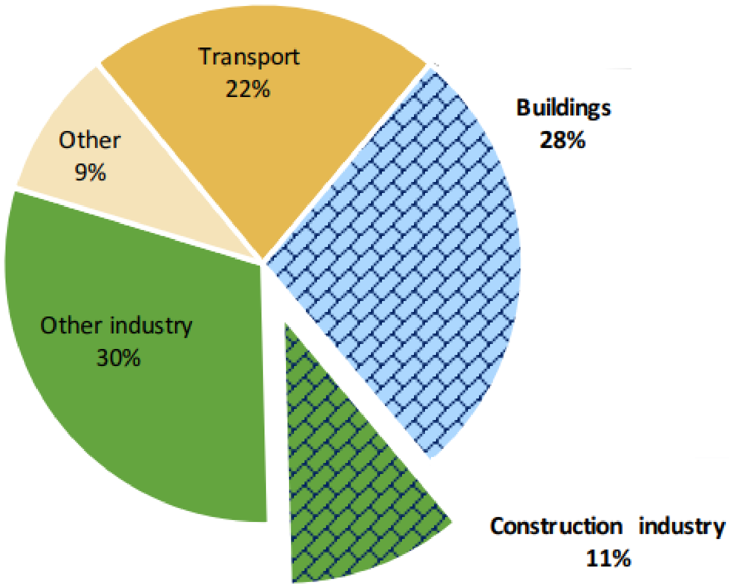


Figure 1. 1 Global CO_2 emission by sector (Abergel et al. 2017)

In recent years, many studies have been conducted on how to reduce building energy use, increase thermal comfort, and reduce greenhouse gas emissions (Suleiman et al. 2015). Since the majority of the residential stock was constructed with no attention to energy efficiency or sustainability and has low indoor comfort conditions, building energy retrofits have become increasingly popular over the past decade as a sustainable approach to improving the energy efficiency of existing buildings (Lee et al. 2019). Energy retrofit measures involve the implementation of modifications to a building's fabric, the engineering systems that provide cooling, lighting, and water heating, using renewable energy systems to offset the residual building energy needs (Hayter and Kandt 2011). They can also require adjustments to how people interact with the building.

In most major cities in Libya including Benghazi, the second most populous city, residential buildings constitute the largest percentage of the total number of buildings and as a result the residential sector consumes more energy than any other (Almansuri 2010; Ali 2018). Unfortunately, existing residential buildings in Libya were built without considering their impact on residents and the environment (Almansuri 2010; Eltrapolsi 2016; Ali 2018; Eltrapolsi et al. 2022). The adoption of architectural solutions that are inappropriate for the climate conditions of Libya has caused significant thermal discomfort inside the buildings, which contributes to a strong dependency on air conditioning for cooling and heating purposes, leading to increased energy consumption (Elaiab 2014; Ali 2018). Heating, ventilation, and air conditioning (HVAC) systems account for nearly half of all energy used in buildings (Alghoul 2017; Ali 2018). Therefore, if the energy consumed by residential buildings could be reduced by the implementation of energy conservation measures and by integrating renewable energy systems with existing buildings, this would have a considerable impact on levels of carbon dioxide released through energy production, resulting in minimizing the consequences of global warming; otherwise, the impact of these buildings on the environment, human comfort, and the economy will be evident.

1.2 Importance of the Research

This study is important due to the fact that the Construction industry in Libya suffers from a lack of building codes, legislation, and regulations, especially regarding thermal requirements and energy conservation. As a result, existing buildings including residential stock have been constructed with no attention to energy efficiency and have low indoor comfort conditions. The growing demand for energy to maintain thermally comfortable indoor conditions in both summer and winter exceeded the country's ability to provide sufficient energy, leading to frequent blackouts (Alghoul et al. 2018; Ali 2018). As the existing residential buildings in Libya, most of which are expected to remain in the future, constitute the largest percentage of energy demand, there is a need to reduce their energy use through thermal refurbishment and retrofitting which will have a substantial impact on reducing energy consumption and carbon emissions. Accordingly, as part of the global effort towards mitigating climate change and global warming, this research aims to identify the optimal solutions for retrofitting existing residential buildings in Benghazi Libya to meet the net zero energy buildings (NZEBs) target by proposing a hybrid retrofit approach. The results of this study can be generalized to many other cities in Libya as they share a similar weather profile and architectural features with Benghazi city.

1.3 Research Gap

A review of the literature was conducted to explore the current knowledge in the field of energy efficiency in residential buildings with a particular focus on the Libyan context. Some of the existing research works focus on Libya in relation to the sustainability of residential buildings in terms of energy consumption and indoor thermal comfort; however, to the best of my knowledge, most of this has been devoted to setting a framework for designing future housing, with limited attention having been paid to retrofitting existing housing stock. In addition, no attempts have been made to investigate the potential of meeting a building's energy needs with renewable energy and meeting the net zero energy buildings (NZEBs) target for housing stock in Benghazi, Libya. Hence, this study aims to fill the gap in the research by identify the optimal solutions for retrofitting the existing residential buildings stock in Libya to meet the net zero energy buildings (NZEBs) target by proposing a hybrid retrofit approach. In addition, embodied carbon reduction using renewable and low-carbon materials such as bio-based insulation materials were previously studied in minor research. Other research including that in the Libyan context employed petroleum-based insulation materials in retrofitting existing residential buildings. Accordingly, this study investigates the effectiveness of biobased insulation materials on energy reduction in the Libyan housing stock.

A major weakness in the literature is represented by the credibility of the energy models, where in most of the studies reviewed, including that on Libya, were carried out without ensuring the reliability of the energy model. This was due to the lack of adequate measured data required for energy model setup and calibration. Consequently, this research includes detailed model calibration based on measured data to ensure the reliability of simulation results.

1.4 Statement of the Research Problem

At present, most residential buildings, not only in Libya but all over the world, tend to consume the most produced energy. Heating, ventilation, and air conditioning (HVAC) systems account for almost half of the consumed energy in buildings in developing countries (El Bakkush 2016; Alghoul 2017). Despite having some of the largest oil fields and wells in the world, since 2013 Libya has experienced a shortage of electricity (Alghoul et al. 2018; Ali 2018). As a result, Libyans suffer from frequent power cuts, especially in the summer and winter seasons due to the increasing demand for energy to operate the HVAC system. The state-owned electricity company has failed in recent years to bring electricity demand and supply into balance (GECOL 2012). Daily power cuts particularly during the heating and cooling seasons can last for up to twelve hours (Alghoul et al. 2018). This suggests that these buildings are no longer thermally comfortable unless air conditioning is used. Thus, people are unable to tolerate living in them and this will inevitably lead to greater expense for the country for the construction of new buildings.

Many studies and efforts have been undertaken to make new and future buildings sustainable and less energy-consuming (Refahi and Talkhabi 2015; Al-Saadi et al. 2017; Alalouch et al. 2019; Monna et al. 2021). Some studies even aimed to achieve a zero-energy building to protect the environment (Albadry 2016; Nader and Alsayed 2016; Khattab 2018; Alyami et al. 2021; GamalEldine and Corvacho 2022; Hamza et al. 2022). Regarding the Libyan context, limited research has been devoted to establishing a method for designing energy efficient residential building and rather less attention has been paid to thermally retrofitting the existing residential stock (Elaiab 2014; El Bakkush 2016; Eltrapolsi 2016; Alghoul et al. 2018; Ali 2018). Since existing residential buildings are expected to remain in the future (Xing et al. 2011; Bienert et al. 2023), it is crucial to retrofit them to lower their energy needs and carbon emissions. Moreover, unfortunately, the Construction industry in Libya suffers from a lack of building codes, legislation, and regulations, especially regarding thermal requirements, and energy conservation and, as a result, energy efficiency in existing residential buildings is now a top priority for Libya's energy policy. This research comes as a step toward achieving this target.

1.5 Research Questions

Having identified the problem of residential buildings in Libya with regard to energy consumption and thermal comfort in the literature review and the current data on the study context the author was driven to set the following research questions:

1- What are the main contributors to energy consumption in existing residential buildings in Benghazi, Libya?

2- What measures can be developed to improve the efficiency of existing housing in Benghazi, Libya?

3- Is it feasible for existing Libyan housing to meet the net zero-energy buildings (NZEBs) target with a combination of thermal refurbishment and using renewable energy?

1.6 Aim and objectives

Although energy retrofitting of existing residential buildings has been adopted in most countries around the world, they have not been applied in some developing countries such as Libya. Hence, this research aims to identify the optimal solutions for retrofitting existing residential buildings stock in Libya to meet the net zero energy buildings (NZEBs) target by proposing a hybrid retrofit approach. To achieve this aim, the following research objectives have been developed.

1. To select representative buildings from different residential building typologies in Benghazi city to investigate different energy retrofit measures.

Study of Libyan residential typology (literature review+ government report)

2. To identify the key contributors to energy consumption in existing residential buildings in Benghazi, Libya.

   a) Literature review

   b) Case study buildings monitoring (empirical study)

   c) Case study buildings modelling and calibration based on actual data (numerical simulation)

   d) Base case model simulation (annual energy consumption profile +heat balance result)

3. To analyses the effect of single and combined retrofit measures on energy and thermal performance during the heating and cooling seasons to determine the optimal energy retrofit scenario for reducing energy consumption without compromising thermal comfort in existing residential buildings of Benghazi, Libya.

   a) Setup for the base case and optimised case (numerical simulation).

   b) Optimisation Simulation (single retrofit measure, combined retrofit measures) (numerical simulation).

   c) Comparison of results between the base case and optimised case (quantitative analysis).

   d) Selection of best case based on performance (quantitative analysis).

4. To investigate the potential of meeting the target of net zero energy buildings (NZEBs) using a renewable energy source.

   Further optimisation to meet the target of net zero energy buildings (NZEBs) by integrating renewable energy (numerical simulation+ quantitative analysis).

1.7 Research Scope and Focus

The focus of this research is limited to investigating the thermal and energy performance of the existing housing stock in the Mediterranean climate of Libya and recommending energy-efficient retrofit measures, with a particular focus on Benghazi city. The retrofit measures will be examined from the perspective of reducing energy consumption and will investigate the potential of meeting the target of the net zero energy buildings (NZEBs) without compromising thermal comfort.

Benghazi is located on the southern coast of the Mediterranean where most of the Libyan population lives, thus allowing the results to be generalized to many other cities in Libya that share a similar weather profile and architectural features. There are three different building typologies in the city namely terraced houses, detached houses (villas), and apartment building. Based on the Urban Planning Agency (UPA), terraced houses constitute the majority of housing stock in Benghazi city (UPA 2009) which means that this type have a great potential for energy conservation. However, in this study, all three building typologies will be included for two reasons. Firstly these figures might have changed since the building census data is dated 2006 (UPA 2009), and there is no current data available. Secondly, all existing dwellings are below modern standards according to both liveability and sustainability criteria (Almansuri 2010).

1.8 Research Structure and Framework

The research is divided into three phases (Figure 1.2): literature review, research studies, and research outcomes. The study is presented in eight chapters as follows:

Chapter One introduces the background of the research, the importance of the research, and the gap in acknowledge. It demonstrates the statement of the research problem, research question, aim, and objectives, and the research scope and focus. Finally, this chapter provides an outline of the structure and framework of the research.

Chapter Two offers a wider picture of the research context (Benghazi, Libya), its location and climate features, housing typology, dominant construction method, and materials. It provides a review of the energy consumption profile, building energy efficiency codes, legislation, and regulations, as well as discussing the potential and future prospects of solar energy in Libya.

Chapter Three provides a general review of relevant knowledge in the research field of building energy retrofit. It starts with an overview of essential understandings of building energy retrofitting, highlighting different energy retrofit measures for residential buildings. Then, a systematic review of the work carried out by other researchers on energy efficiency in existing residential buildings in Libya and neighbouring Mediterranean countries. Finally, the gaps in the present knowledge related to energy efficiency in existing residential buildings in Libya are then identified.

Chapter Four presents an overview of the research methods adopted in this research, as well as the analytical framework. The criteria of the Case Study selection are highlighted, followed by an explanation of the monitoring equipment and methods for data collection. This chapter goes on to give a description of the methodologies for calibrating and simulating the Case Study models. The optimisation approach is also explained in final section of this chapter.

Chapter Five involves the buildings survey and monitoring related work. An initial analysis of the collected data is carried out to provide a general understanding of the energy performance and indoor thermal conditions of the Case Study buildings.

Chapter Six is dedicated to the results and analysis of the calibration simulation study of the three Case Study buildings. To ensure that the building models closely represent actual buildings, and to obtain precise simulation outcomes, monthly energy consumption calibration, hourly energy consumption calibration, monthly zone temperature calibration, and hourly zone temperature calibration based on actual data are adopted and presented in this chapter.

Chapter Seven uses the calibrated models of the Case Study buildings to assess different energy retrofit measures (single retrofit measures and combined retrofit measures) to define the optimum solutions for achieving energy use reduction without compromising thermal comfort. After that, further optimisation is carried out to meet the requirements of the net zero energy buildings (NZEBs) by integrating renewable energy. The final section of this chapter discusses the main findings of this research.

Chapter Eight, the concluding chapter presents an overview of the findings of the research work and its implications to fulfilling the research aim and objectives. It is a synthesis of the research findings from the literature review, and research work conducted to inform the optimal design solutions to retrofit the existing residential buildings as well as designing energy efficient dwellings for the future. It summarises the various contributions to knowledge and highlights how the research has bridged the identified research gaps. This chapter also addresses the research limitations and outlines a potential direction for future research.

1.9 Chapter Summary

This chapter provides an overview of the research, including the research background, the importance of the research, aim, objectives, research questions, and the research scope and focus. It concludes with an outline of the structure and framework of the research. The next chapter provides an overview of existing data on the research context.

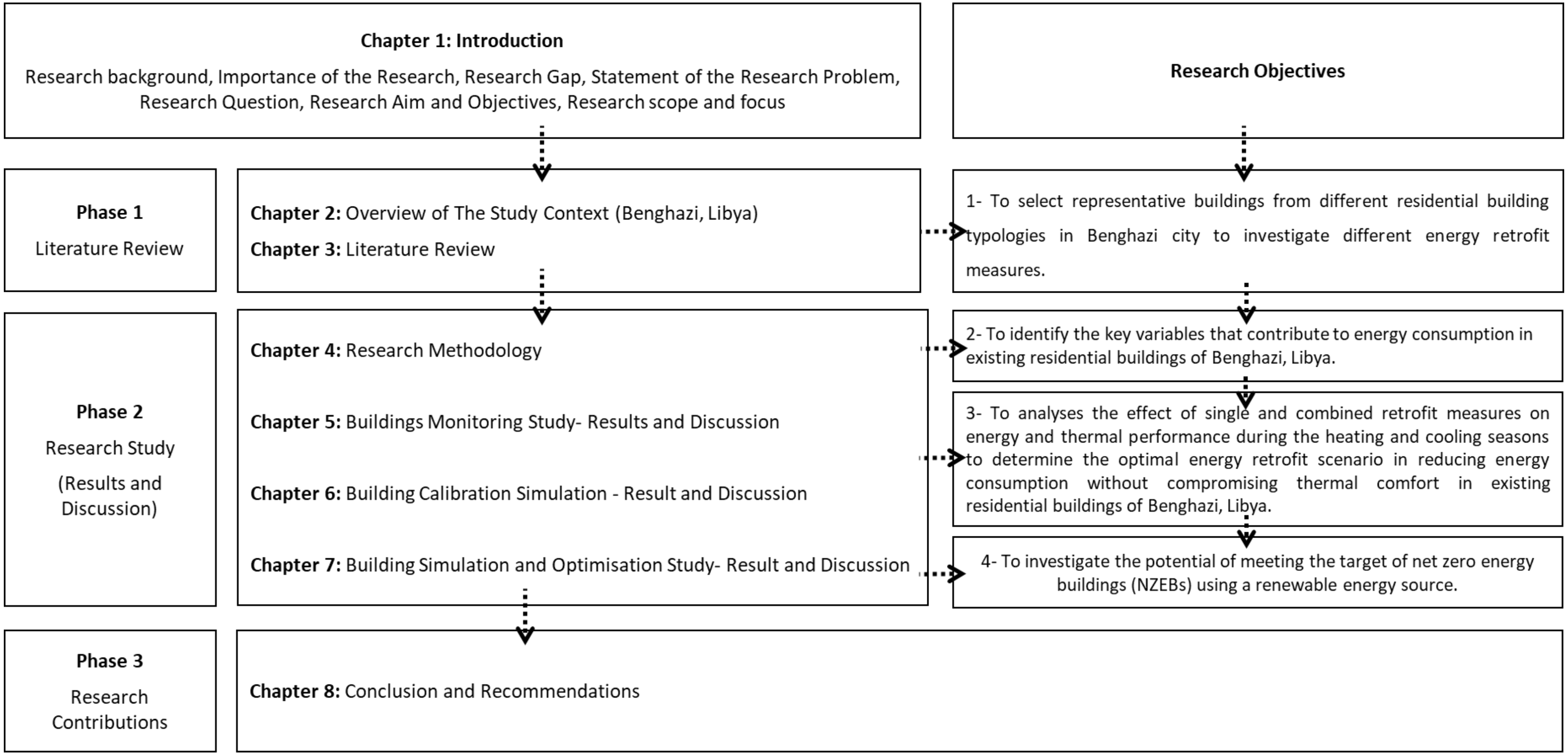


Figure 1. 2 Research structure

Chapter 2: Overview of The Study Context (Benghazi, Libya)

2.1 Introduction

This chapter provides an overview of existing data on the research context. It presents data on the location and climate features of the city of Benghazi, provides information on the housing typology, dominant construction method, and materials. It provides a review of the energy consumption profile, building energy efficiency codes, legislation, and regulations, as well as discussing the potential and future prospects of solar energy in Libya.

2.2 Location and Climatic Parameters of Benghazi City

Libya is situated on the Mediterranean coast in northern Africa, encompassing a geographical area of 1,750,000 km^2 and lying between latitude 20° and 34° N and longitude 10° to 25° E. It is characterised by a Mediterranean climate in the north, harsh desert climate in the south and semi-arid climate in the transition area between the Mediterranean and desert zones. Benghazi, Libya's second capital city, is located in north-eastern Libya and had a population of 632,937 people in 2019, with a population density of approximately 2,000/km^2 (UPA 2009). According to Köppen-Geiger climate classification map, the contrast of sea and desert between the humid Mediterranean coast and the semi-arid desert areas is the most striking characteristic of Libya's climate (Kottek et al. 2006). Figure 2.1 shows the Köppen climate classification for the climate of Libya.

The desert area of Libya is characterised by a cool winter, with temperatures averaging 27 °C in the daytime, but at times dropping below freezing at night; and very hot summers with average daytime temperatures of 50°C. A wet, rainy winter and a hot, dry summer define the Mediterranean climate along the coast, where Benghazi and other major cities are located. The warmest months are July and August, with average temperatures of 34°C, with the potential to reach a maximum of 45°C, while the coolest months are January and February, with average temperatures of 8°C. The annual rainfall in Benghazi is very low, at approximately 250 mm, with annual average humidity of 58% (Meteoblue 2021; Weatheratlas 2021) (Figures 2.2- 2.3).

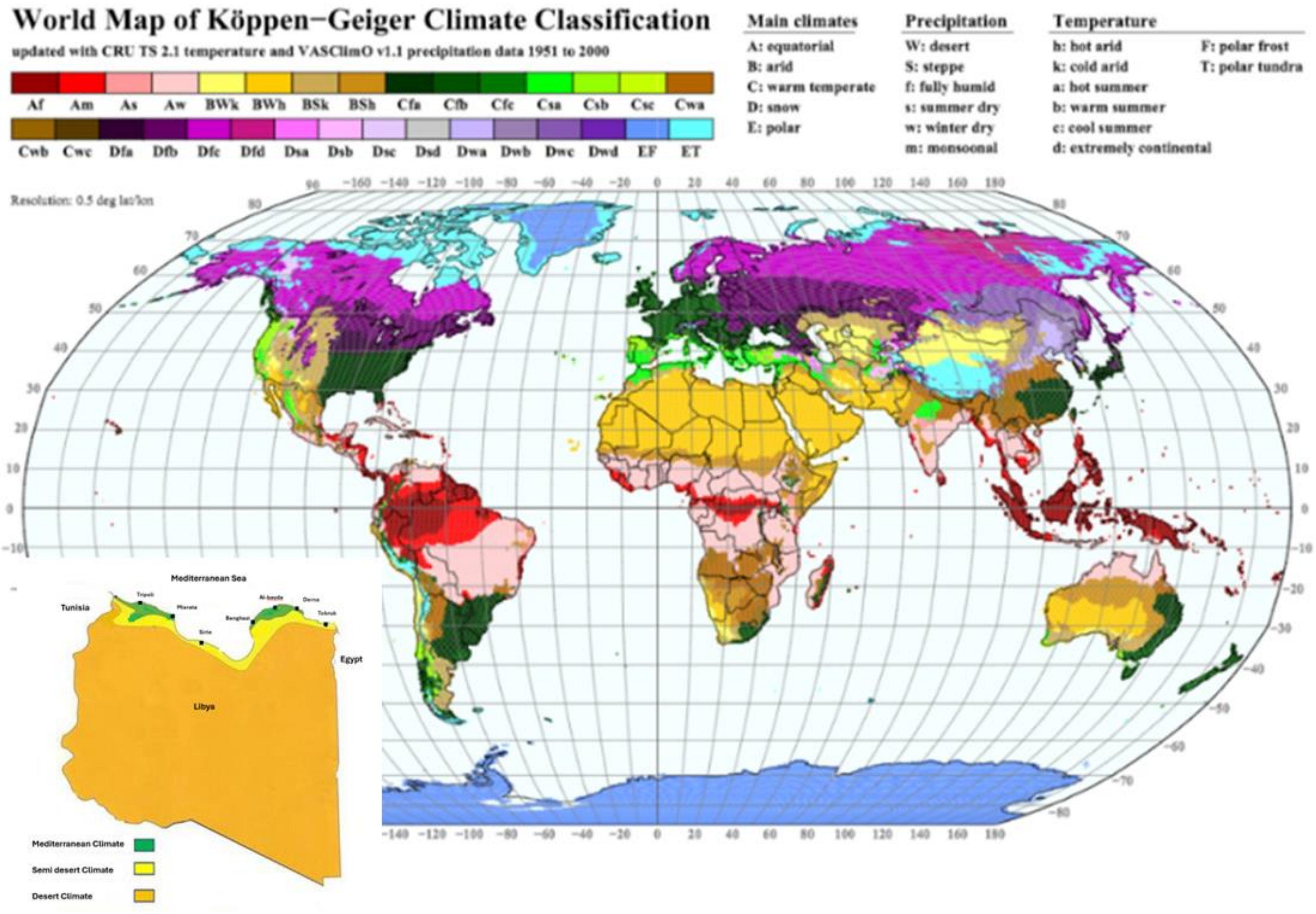


Figure 2. 1World map showing the Köppen-Geiger climate classification for Libya (Kottek et al. 2006)

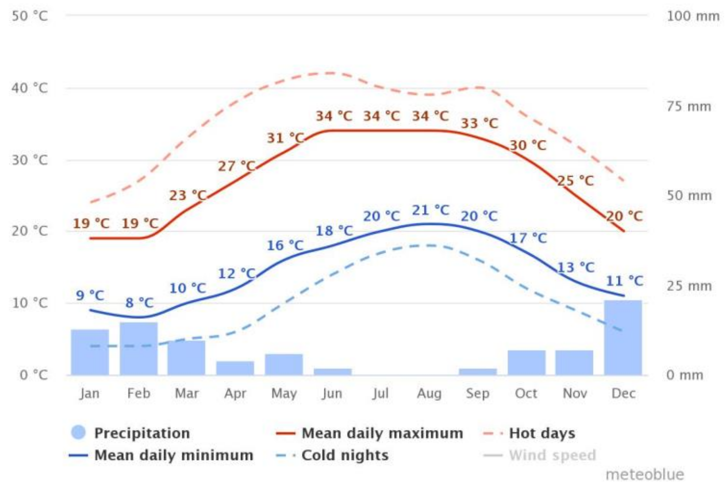


Figure 2. 2 Monthly average dry bulb temperature, Benghazi, Libya (Meteoblue 2021)

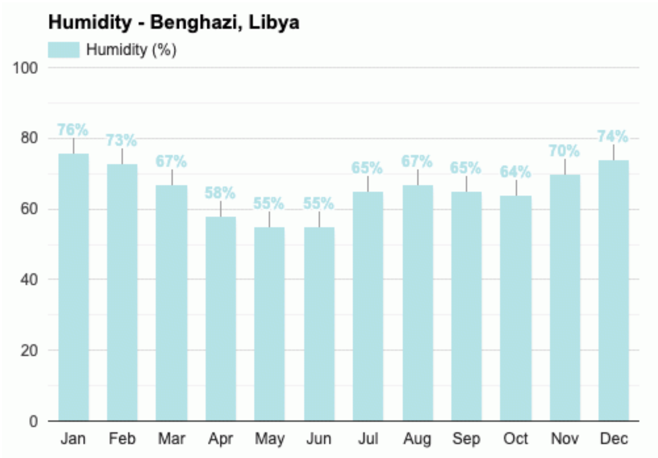


Figure 2. 3 Average monthly relative humidity, Benghazi, Libya (Weatheratlas 2021)

2.3 Energy Consumption of Residential Buildings in Libya

According to the World Bank (2013) Libya is one of the highest-ranked countries in terms of energy consumption (Figure 2.4). Table 2.1 illustrates that Libya ranks seventh in those Arab countries located in the Middle East and North Africa (MENA countries) and thirty-seventh in the world in terms of energy consumption per capita (Al Shamsi 2017).

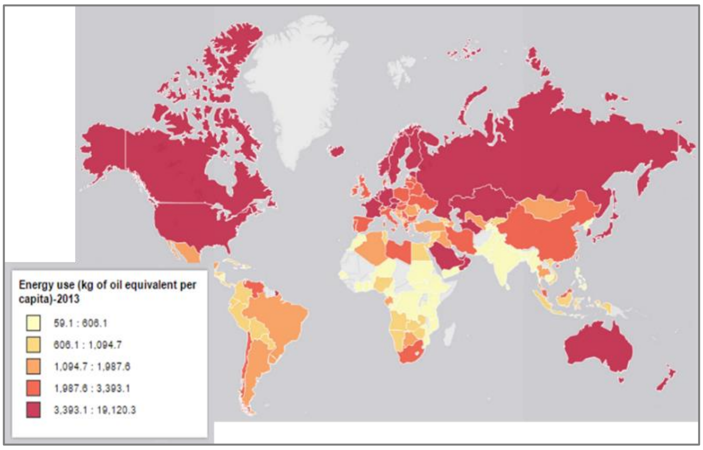


Figure 2. 4 World energy consumption per capita, 2013 (WorldBank 2013)

No.	World ranking	Country	Energy / capita /year [kgoe/a]	GJ / capita /year	kWh/capita / year	
1	3	Qatar	12799.4	537.58	17041.2	High consumption
2	4	Kuwait	12204.3	512.58	16248.8	
3	7	United Arab Emirates	8271.5	347.4	11012.6	
4	8	Bahrain	7753.7	325.65	10323.2	
5	10	Oman	7187.7	301.88	9569.7	
6	15	Saudi Arabia	6167.9	259.05	8212	
7	37	Libya	3013	126.54	4011.5	
8	38	Israel	3005.4	126.23	4001.3	
9	41	Iran	2816.8	118.3	3750.2	
10	67	Lebanon	1526.1	64.1	2031.8	Mid
11	68	Turkey	1445.1	60.69	1924	
12	76	Jordan	1191.4	50.04	1586.2	
13	78	Iraq	1180.3	49.57	1571.4	
14	79	Algeria	1138.2	47.81	1515.5	
15	83	Syria	1063	44.64	1415.2	
16	86	Tunisia	912.8	38.34	1215.3	
17	87	Egypt	903.1	37.93	1202.4	
18	112	Morocco	516.7	21.7	687.9	Low
19	124	Sudan	370.9	15.58	493.9	
20	131	Yemen	297.9	12.51	396.6	

Table 2. 1 Energy consumption per capita for different MENA countries (Al Shamsi 2017)

Due to the lack of building codes, legislation, and regulations specifically about thermal requirements and energy conservation in Libya, existing and newly-constructed residential buildings have poor indoor thermal conditions, requiring a large amount of energy to run air conditioning and provide a comfortable indoor environment (Almansuri 2010; Elaiab 2014; El Bakkush et al. 2015; Eltrapolsi 2016; Ali 2018). Between 2000 and 2010, according to the General Electricity Company of Libya (GECOL), electricity generation in Libya increased by 50% (GECOL 2012).

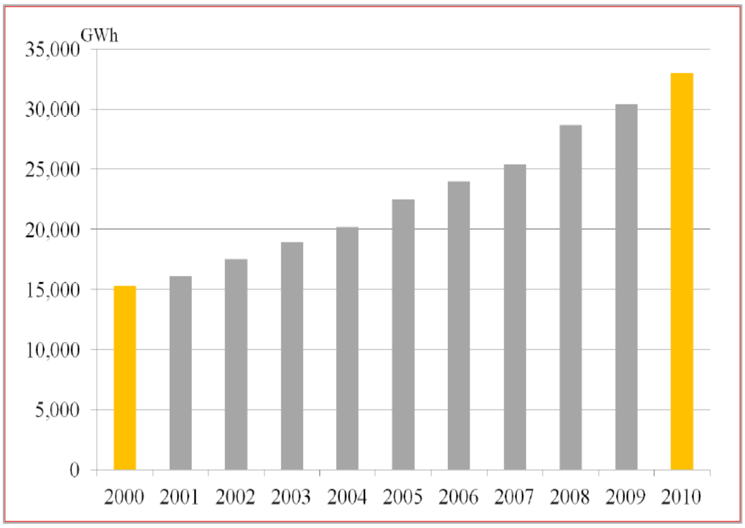


Figure 2. 5 Electricity generation in Libya, 2000 to 2010 (GECOL 2012)

Electricity is the main source of power for the building operations sector in Libya. The residential sector load, as illustrated in Figure 2.6, constitutes more than a third of total electricity consumption (Tawil et al. 2018) and almost half of this is used for cooling (El Bakkush 2016; Ali 2018). Although Libya is an oil-producing country, it is experiencing an energy crisis as a result of extensive use of conventional energy based on the increase in building energy consumption, which has resulted in depletion of those resources (El Bakkush 2016).

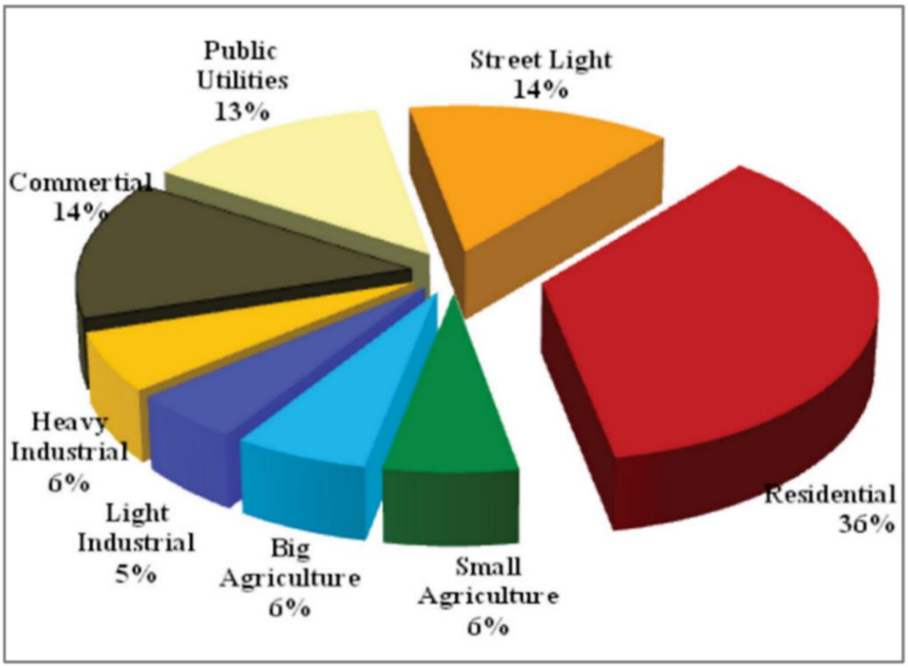


Figure 2. 6 Electricity consumption by sector in Libya (Tawil et al. 2018)

Because existing residential buildings account for the majority of energy consumption, improving their energy efficiency through the implementation of various energy-saving measures is crucial to reducing energy consumption while maintaining thermal comfort, and thus is an effective approach to mitigating environmental impacts such as global warming and ozone layer depletion (Ali 2018).

2.4 Libyan Building Energy Efficiency Codes, Legislation, and Regulations

Building energy codes and standards are an important policy tool for increasing building energy efficiency (Iwaro and Mwasha 2010). They provide certain energy efficiency characteristics for building technologies including the building envelope, HVAC systems and lighting, as well as water heating systems (Cox 2016). The first regulations, standards, building codes, construction materials, and strategies were introduced to the Libyan construction market during the period of Italian colonialism (1911-1943) and then British and French administration (1943-1951) (Salah and Bloomer 2014). Although a building code has been introduced in Libya, it does not address energy efficiency in buildings or climate-responsive design requirements (El Bakkush 2016). Table 2.2 illustrates the status of low carbon buildings (LCB) and building energy regulations in MENA countries and shows that Libya has no standards for energy efficiency in buildings (Al Shamsi 2017).

No		Country	Insulation Standard	Energy Efficiency Standard of Buildings	Energy Labelling Standard	Energy Audits Standard	LCB Status
1	Non-GCC Countries	Algeria	U/D	U/D	-	N/I	N/I
2		Egypt	N/I	V	M	V SUBSIDISED	AG
3		Iran	N/I	V - OFFICES	N/I	N/I	N/I
4		Iraq	N/I	N/I	N/I	N/I	N/I
5		Israel	M	V	M	V	Es (Europe)
6		Jordan	M	U/D	N/I	N/I	Em
7		Lebanon	V	V	U/D	N/I	Pr
8		Libya	N/I	N/I	N/I	N/I	AG
9		Morocco	N/I	U/D	U/D	N/I	Pr
10		Palestinian	V	V	N/I	N/I	Pr
11		Syria	V	V	V	N/I	Pr
12		Tunisia	M	M	M	N/I	AG
13		Turkey	M	M	N/I	N/I	Es (Europe)
4		Yemen	N/I	N/I	N/I	N/I	N/I
1	GCC Countries	(Abu Dhabi)	N/I	U/D	M	N/I	Es
2		(Dubai)	N/I	U/D	M	N/I	Es
3		Qatar	U/D	U/D	U/D	U/D	Em
4		Bahrain	N/I	N/I	N/I	N/I	Pr
5		Kuwait	N/I	M	N/I	N/I	Pr
6		KSA	N/I	U/D	N/I	N/I	Pr
7		Oman	N/I	N/I	N/I	N/I	AG

AG Associated Group; Em Emerging; U/D Under development; Es Established; GB Green Building; V Voluntary; GBC Green Building Council; M Mandatory; **LCB Low carbon buildings**; N/I No information; Pr Prospective

Table 2. 2 Status of building energy regulation in MENA countries (Al Shamsi 2017)

The construction industry in Libya suffers from a lack of building codes, legislation, and regulations, in particular in relation to thermal requirements and energy conservation, and this has led to the construction of buildings with no regard for energy efficiency beyond what is required by international energy codes. Accordingly, it is critical for Libya to promote energy efficiency and protect the environment; establishing a residential building code is the first step toward achieving this goal (El Bakkush 2016; Bodalal et al. 2017; Tawil et al. 2018).

2.5 Solar Energy Potential in Libya

The present energy sources in Libya are mostly unsustainable, and the present oil reserve is expected to last for only the next thirty years (Mohamed and Masood,2018). However, Libya has strong potential for renewable energy (Almaktar and Shaaban 2021). Photovoltaic and solar thermal systems are becoming more popular for generating electricity in the country (Hewedy et al. 2017). Libya has an excellent solar profile, with an average annual sun duration of more than 3500 hours. On a horizontal surface, the daily average solar radiation ranges from 7 to 7.8 kWh/m^2/day for the summer months, and from 2 to 7 kWh/m^2/day for the rest of the year (Mohamed 2013; Hewedy et al. 2017). As presented in Figure 2.7, an average annual solar radiation of 2000 kWh/m^2/y makes the production of electricity from photovoltaic (PV) systems economically feasible for Libya when compared with conventional sources of energy (Mohamed 2013; Hewedy et al. 2017).

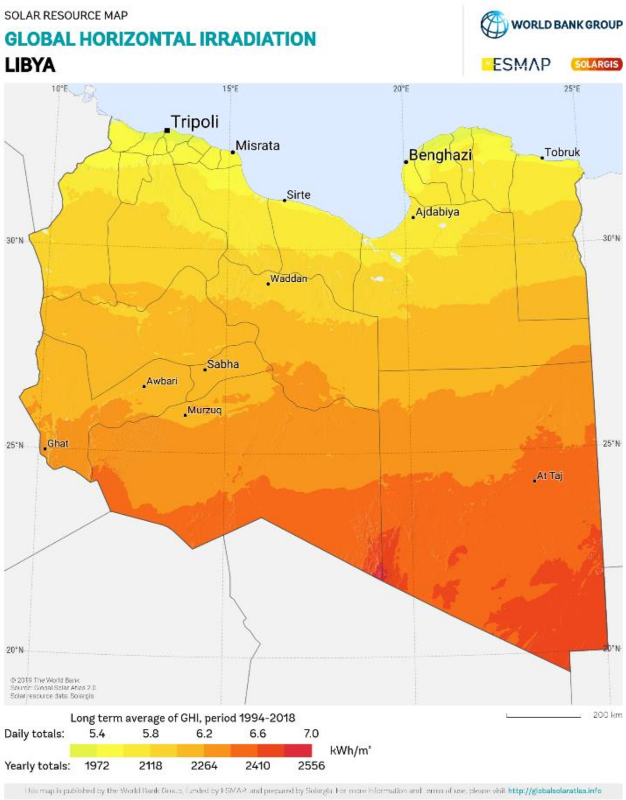


Figure 2. 7 Global horizontal irradiation map of Libya (The World Bank Group 2019)

In Libya, solar energy is used for solar electric (PV) and solar thermal applications. The use of solar energy for domestic water heating and space cooling and heating has proved to be viable in Libya. A study by Uppal and Muneer (1984) conducted on a house located in the city of Kufra shows that a water-lithium bromide absorption system can provide summer air conditioning in the hot environment of Libya, where there are difficulties with the supply of electricity and fossil fuels (Uppal and Muneer 1984). Almaktar et al. (2021) conducted economic and environmental research on a grid-connected photovoltaic (GCPV) system for a house located in Benghazi. Using HOMER simulation software, a small 5 kW grid-connected PV system was designed to meet the 20 kWh average daily energy demand of the house. The results reveal that the PV system not only meets the energy needs of the building but can also sell clean energy back to the grid. For this reason, the application of solar energy in existing dwellings in Libya is highly encouraging, and is the most effective choice available to the country when looking to the future (Almaktar et al. 2021).

2.6 Residential Building Industry in Libya

Prior to 1960, as Libya was emerging from the Italian occupation, the industrial sector was of limited scale because of shortages in funds and raw materials, and the majority of the population lived in tents and huts made of zinc sheets or palm tree leaves (Amer 2007; Ngab 2007). After the discovery of oil in 1964 however, the economy was transformed from a primitive economy to an oil-based economy (Amer 2007). The focus of development policy was mostly on urban areas. As a result, large cities such as Tripoli and Benghazi improved more than any other area in the country. Based on these developments, people in the countryside were attracted to move to these cities (Amer 2007). In the 1970s, the country experienced a massive growth in the scale and volume of construction activities, particularly in housing, and by the end of the 1970s, Libya had become the world's leading per capita consumer of cement (Ngab 2007). In Libya's construction industry, cement and its related products, such as concrete, bricks, and other materials, have become the dominant basic construction materials (Salah and Bloomer 2014). Reinforced concrete roofs, limestone block walls or cement block walls, and concrete stone foundations form the construction systems commonly used in Libya. In the 1970s, residential buildings were constructed with reinforced concrete roofs and limestone block walls, and from the eighties until the present time, residential buildings have been built from concrete block walls and a reinforced concrete slab or hardy slab to construct the roof (Almansuri 2010; Tawil et al. 2018). In addition, up to and including the present time, insulation materials have not been used in housing construction (Elaiab 2014; El Bakkush et al. 2015; Ali 2018). Table 2.3 presents the properties of the common construction materials in existing residential buildings in Libyan cities, including Benghazi city based in previous research (Gabril 2014; Ali 2018).

Table 2. 3 Construction materials used in existing residential buildings in Libya (Gabril 2014; Ali 2018)

Material description	Thickness mm	Conductivity W/m deg. C	Density Kg/m³	Specific heat J/(Kg deg. C)
Contemporary construction materials for concrete walls				
Light plaster	3	0.16	600	1000
Cement screed	20	1.4	2100	650
Hollow concrete block	150	1.06	1950	650
Cement screed	20	1.4	2100	650
Light plaster	3	0.16	600	1000
U-value	**2.648 W/m²k**			
Contemporary construction materials for limestone walls				
Light plaster	3	0.16	600	1000
Cement screed	20	1.4	2100	650
Limestone block	200	1.5	2180	720
Cement screed	20	1.4	2100	650
Light plaster	3	0.16	600	1000
U-value	**2.707 W/m²k**			
Contemporary construction materials for roofs (hardy slab)				
Floor tiles	10	0.6	500	750
Cement mortar	20	1.4	2100	650
Bitumen felt	6	0.5	1700	1000
Heavy mix	100	1.4	2100	653
Hollow brick	100	0.44	1500	650
Cement screed	20	1.4	2100	650
U-value	**2.016 W/m²k**			
Contemporary construction materials for roofs (reinforced concrete slab)				
Floor tiles	10	0.6	500	750
Cement mortar	20	1.4	2100	650
Bitumen felt	6	0.5	1700	1000
Reinforced concrete	200	1.4	2400	880
Cement mortar	20	1.4	2100	650
Light plaster	3	0.16	600	1000
U-value	**2.369 W/m²k**			

As mentioned earlier in this chapter, Libya has no energy code for buildings to investigate whether the thermal characteristics of building materials meet energy efficiency requirements. However, based on the residential energy code in Egypt, and the residential building codes for Arab countries which have a similar climate classification to Libyan cities, the thermal transmittance of a building's walls and roof should be no more than 1.1 W/m²K and 0.6 W/m²K respectively (Robertson 1998; Hanna 2010). Based on Passivhaus retrofit standards, all opaque surfaces of the building must have U-values of 0.5 W/m²K or less (Passivhaus 2021). Therefore, it is apparent from Table 2.3 that the U-values of the construction materials of existing residential buildings in Libya do not meet the U-value requirement of the energy codes of Arabic countries, and nor do they meet energy efficient building standards. Therefore, thermal refurbishment of the roofs and walls of existing dwellings in Libya may have a considerable impact on reducing energy consumption and improving indoor thermal comfort.

2.7 Vernacular and Contemporary Dwellings in Libya

Vernacular dwellings in Libya are classified based on the natural conditions, local climate, and culture (Gabril 2014). Libya has three different prototypes of traditional vernacular dwellings: open courtyards in the coastal area; earth-sheltered dwellings in the mountains; and compact dwellings in the desert area (Amer 2007; Gabril 2014). The open courtyard, however, makes up the majority of dwellings and can be found across Libya's coastal region, where the major cities are located, from Darna and Benghazi in the east to Tripoli in the west (Almansuri 2010; Gabril 2014; Ali 2018). Similarly, contemporary dwellings in Libya are classified into three different typologies: terraced houses, detached houses and apartment buildings; however, contemporary dwellings have been built without consideration of socio-cultural and environmental values (UPA 2009; Almansuri 2010; Ali 2018). The difference between vernacular and contemporary dwellings in Libya can be categorised based on two factors: socio-cultural factors, and environmental factors.

2.7.1 Socio-Cultural Factors

Vernacular dwellings in Libya were developed based on the socio-cultural, and religious values of the Arab Muslim regions (Almansuri 2010; Elwerfalli 2017; Ali 2018). These values play an important role in guiding and directing people's behaviour and lifestyle in both internal and exterior environments (Almansuri 2010). Most of a family's daily activities and celebrations take place within the house. The family's cultural demands affect the house's spatial arrangement: the courtyard is at the centre of the house, surrounded by the building and its rooms. Windows open onto the courtyard, for privacy reasons, and to provide lighting and ventilation. Adequate space is provided in the courtyard for most activities of daily living and housework, as well as meeting the family's cultural and social occasion requirements (Amer 2007). As a result, these social requirements are met in traditional dwellings. On the other hand, there are socio-cultural problems emerging from the new living conditions of Libya's contemporary housing, such as lack of privacy, noise, and a lack of children's play spaces (Emhemed 2005; Amer 2007). Furthermore, the cultural and social backgrounds of the occupants are rarely considered. For instance, outdoor areas are used instead of indoor courtyards. Windows are oriented to the street making them less responsive to the occupants' social, privacy, and thermal comfort needs (Elaiab 2014; Ali 2018). Despite the presence of the courtyard element in some contemporary houses, this is small in area and does not meet the socio-cultural needs of the residents, serving mainly for providing lighting and ventilation as well as for utility functions (Gabril 2014). For the reasons stated above, all family activities have moved inside the house, resulting in higher levels of energy consumption.

2.7.2 Environmental Factors

As mentioned earlier in this chapter, vernacular dwellings in Libya were developed based also on environmental factors. The dense urban fabric as shown in Figure 2.8 helps to minimise the harsh summer sun, protect against severe temperatures and sandstorms, and reduce the thermal load on building envelopes (Elwerfalli 2017; Eltrapolsi et al. 2022). Courtyard houses are typically built in rows, with only the front facing the narrow streets, and the other sides attached to adjacent housing. The building envelope (wall and roof) of the traditional dwelling was made of high thermal mass, very thick materials that were locally available, such as sand, stone, mud and sun-dried brick (Amer 2007). The walls were more than 70 cm thick with shaded voids and small windows, while on the roof, palm-tree trunks covered by a layer of mortar and a layer of mud were used as beams. These materials offer a high degree of resistance to the heat and contribute to a comfortable indoor environment. Roofs and external surfaces were also painted white to reflect solar radiation and to reduce solar gain (Almansuri 2010). This allowed outdoor conditions to have only a limited influence on indoor temperature, while securing a comfortable indoor environment by providing night cooling during the day in summer and retaining day heat during the night in winter (Almansuri 2010). The openings in these buildings are small in size to reduce heat gain, and are inward-looking, towards the courtyard, with scarcely any openings in the exterior walls. The rooms rely almost entirely on the courtyard for light and air circulation (Amer 2007). Although these features are well addressed in Libyan vernacular housing, most do not exist in contemporary houses. The urban fabric of contemporary areas is characterised by a grid pattern and wide straight streets, leading to greater exposure to solar gain (Mohamed 2013). Moreover, despite the important role of the courtyard, it is no longer employed. In contemporary dwellings, walls are usually made of 20 cm thick limestone or hollow concrete blocks with a regular mix of cement, sand, and coarse aggregate, while the roof is usually constructed from hardy slabs or reinforced concrete (concrete with steel bars), which are less responsive to climatic conditions (Elaiab 2014; Ali 2018). Moreover, up to and including the present time, insulating materials remain unused in housing construction (Elaiab 2014; El Bakkush 2015; Ali 2018), which means that the building envelope has less resistance to heat flow. As a result, the building's indoor temperature is more affected by outdoor conditions compared to vernacular buildings made from materials with a high degree of resistance to heat transfer (Almansuri 2010; Ali 2018).

Figure 2. 8 Courtyard house within the compact fabric of the old city of Tripoli (Eltrapolsi et al. 2022)

2.8 Contemporary Libyan Housing

After the discovery of oil in the 1960s, Libya, as with other developing countries, experienced considerable social and economic changes on many levels, and especially in terms of housing development (Ali 2018). Figures 2.9-2.10 show construction developments in the city of Benghazi during and after the 1960s, most of which are housing projects.

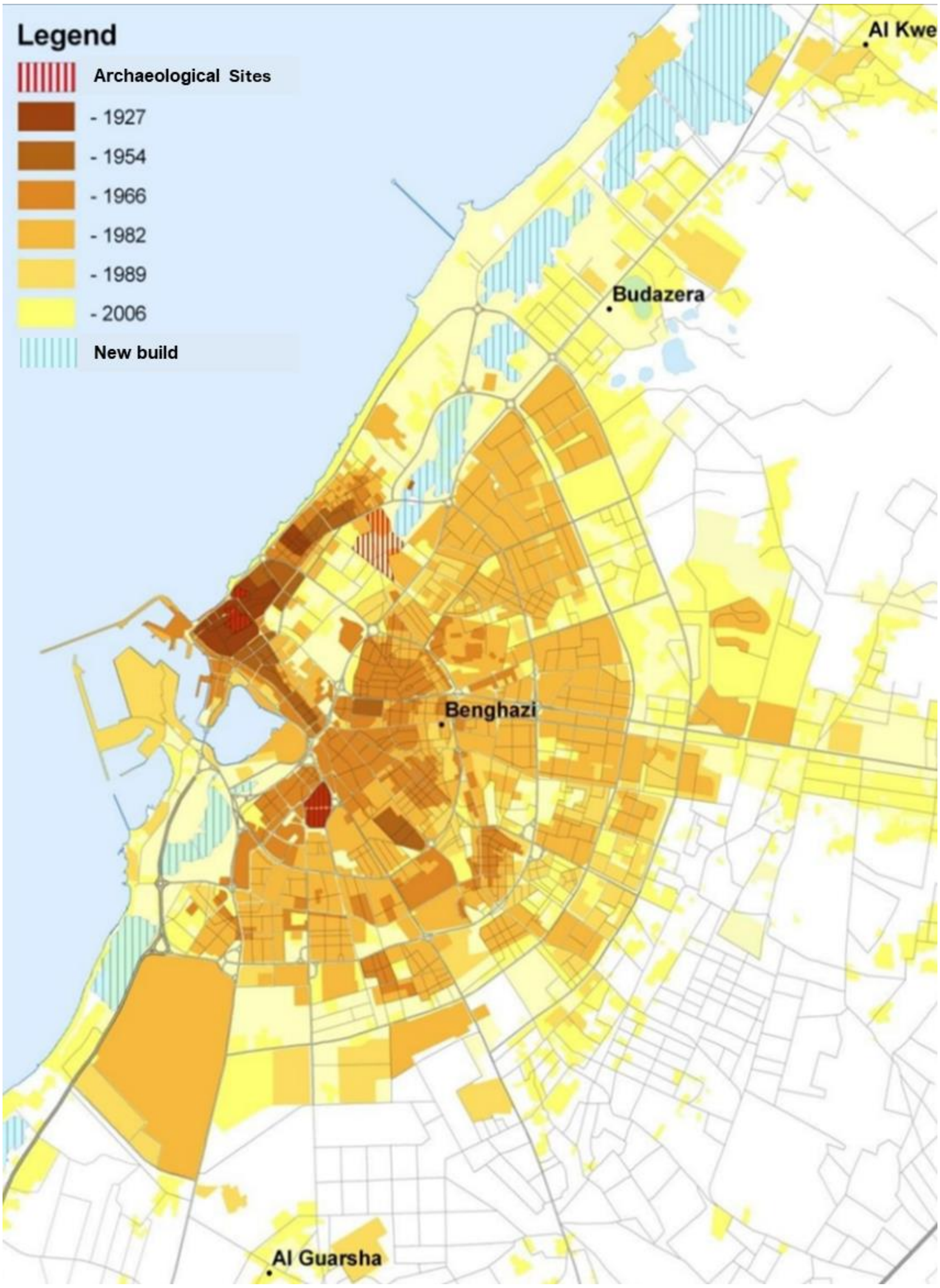


Figure 2. 9 Spatial development of Benghazi (UPA 2009)

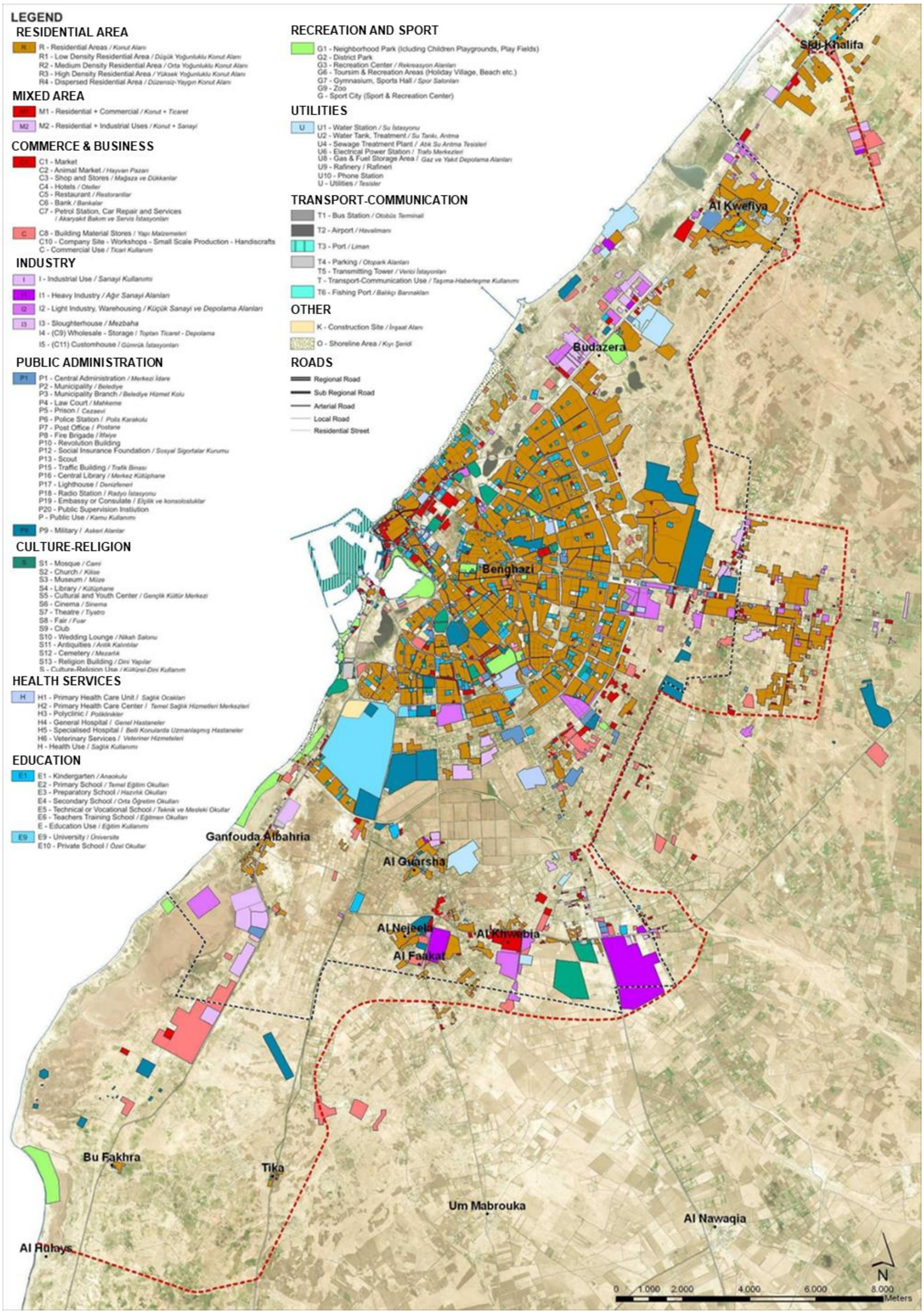


Figure 2. 10 The Benghazi Metropolitan area: existing land use (UPA 2009)

Migration from rural areas and neighbouring countries led to an increase in demand for housing, and more apartment buildings were built. However, apartment buildings have failed to satisfy social and functional needs and people would rather live in single-family houses than apartment buildings (Almansuri 2010). As a result, the single-family house solution emerged, to provide high-level architectural solutions that allow the incorporation of functional relationships between the dwelling and the social requirements of the occupants, in addition to providing direct access to vehicles and services for each house and providing a unique open space for each group of residents. According to the Urban Planning Agency (UPA), the majority of terraced houses were constructed in the 1970s, and this continued until the early 1980s, when a more modern type of accommodation emerged, which is the detached house (villa type), that is still built today (UPA 2009).

2.8.1 Contemporary Housing Typology in Benghazi

According to a 2006 building survey, the Benghazi Metropolitan has 99,968 housing units. Housing zones, excluding mixed-use areas, occupy 5,057 hectares, accounting for 48% of total built land (UPA 2009). Residential areas vary in terms of construction form and pattern, density, and the quality and standards of public services and infrastructure. Residential buildings in the Benghazi Metropolis comprise three major types: terraced houses, detached houses (villas), and apartment buildings (UPA 2009). According to the building census of 2006, terraced houses account for 69.7% of the existing housing stock, while villas and apartment buildings constitute the remaining stock, at 20.7% and 9.6%, respectively (Table 2.4). This picture may have changed, since the building census data is dated 2006. Moreover, there is no recent data available.

Table 2. 4 Housing stock in the Benghazi Metropolis – 2006 (UPA 2009)

Housing Type	Number of Buildings	% of Buildings	Number of Dwelling Units	% of Dwelling Units
House (Haush)	41,700	69.7	41,700	41.7
Villa	12,356	20.7	12,356	12.3
Apartments	5,739	9.6	45,912	46.0
Total	**59,795**	**100.0**	**99,968**	**100.0**

2.8.1.1 Terraced House (Row House or Altered Courtyard House)

The new government of Libya in the early years of the 1970s gave high priority to housing projects (Amer 2007). The terraced houses that emerged during this period represented a dramatic transformation in the built environment of the major cities of Libya. In Benghazi, terraced houses constitute the highest percentage of existing housing stock. They are situated in areas with less compact urban forms and moderate density. The layout and arrangement of residential blocks has produced green space, which is praised for enhancing environmental quality. The houses were planned on areas of 120-150 m², and are one or two-storey buildings, with two or more rooms that open onto a private courtyard for lighting and ventilation (Gabril 2014) (Figure 2.11).

The courtyard is usually square or rectangular in form and positioned to the centre, front, or back of the house. This modification is seen as the beginning of the end of the open courtyard. The design of the first and second floors include the same spaces: three bedrooms, a living room, a guest reception room, and bathrooms. In addition, there is no consistency in style amongst terraced dwellings, wherein diverse styles of windows, lintels, and arches are employed in the buildings' facades (Ali 2018). With regard to construction materials, terraced houses are constructed using reinforced concrete frameworks, flat reinforced concrete roofs and columns, and uninsulated single-layer walls using hollow concrete blocks or limestone blocks (Almansuri 2010; Gabril 2014; Eltrapolsi 2016; Ali 2018).The exterior walls of the terrace house are adjacent to and shared by the attached houses. However, the front elevation faces the street and is exposed to different solar radiation intensities based on its direction. The courtyard walls can also be considered as exterior walls. Some terraced houses have a back yard, which leads to exposure to more solar radiation. Due to changes in the Libyan government's policies, this type of dwelling has not been built since the beginning of the 1980s (Amer 2007).

Figure 2. 11 Compact form of grid pattern and altered courtyard buildings (UPA 2009; Mohamed 2013)

2.8.1.2 Detached Houses (Villa)

Due to the failure of public housing construction programmes at the beginning of the 1980s to meet national housing goals, the government began to encourage citizens, and public and private companies to increase their investment in housing production, by providing land for building, offering access to construction materials, and giving housing loans (Amer 2007). The second housing type described is a detached house known as a 'villa'. It is a modern style of accommodation in Libya and replaces the older style of the terraced house. The villa type of house, which accounts for 12.3% of all dwelling units, usually consists of one or two storeys and is surrounded by a garden, as shown in Figure 2.12, to provide lighting and ventilation for the interior spaces (Mohamed 2013). This is built on an average area of 500 m² (around 250m² for each floor), and is enclosed by a high masonry wall in order to ensure privacy (Gabril 2014).

Figure 2. 12 Design layout of villa type (UPA 2009; Mohamed 2013)

This model has more surfaces exposed to solar radiation and external climatic conditions compared to the terraced model. As a result, it may be more energy-consuming. In addition, this model has received much criticism because it does not contain a courtyard, which is required to fulfil the functional and social needs of the occupants. The courtyard here is replaced by surrounding open space which is not used due to lack of privacy and exposure to solar radiation during the day. The ground floor is frequently specialised for use for living, dining, and hosting visitors, while the bedrooms are located on the first floor. Reinforced concrete roofs and columns, and single-layer walls made of hollow concrete blocks with no insulation are also used as construction materials in this type of residence (Ali 2018).

2.8.1.3 Multi-Storey Apartment Buildings

Multi-storey apartment buildings are scattered throughout the city. They are classified into two categories: the low-rise apartment building; and the high-rise apartment building. The high-rise apartment buildings consist of 5-12 storeys and generally have 2-4 apartments on every storey. The low-rise apartments are from 2-4 storeys high and usually have two apartments on every floor, which means that each apartment has a large wall area exposed to solar radiation and external conditions (Figure 2.13). Each flat has an average area of about 90-150 m^2, including 1-3 bedrooms, a living area, kitchen, guest room, and 1-2 bathrooms (Mohamed 2013). As with the other types of dwelling, reinforced concrete roofs and columns, and single-layer hollow concrete blocks with no insulation are the most common materials used in constructing these buildings (El Bakkush 2016). Despite their existence in the apartment buildings, verandas and balconies are kept closed or used only for storage, due to lack of privacy (Ali 2018).

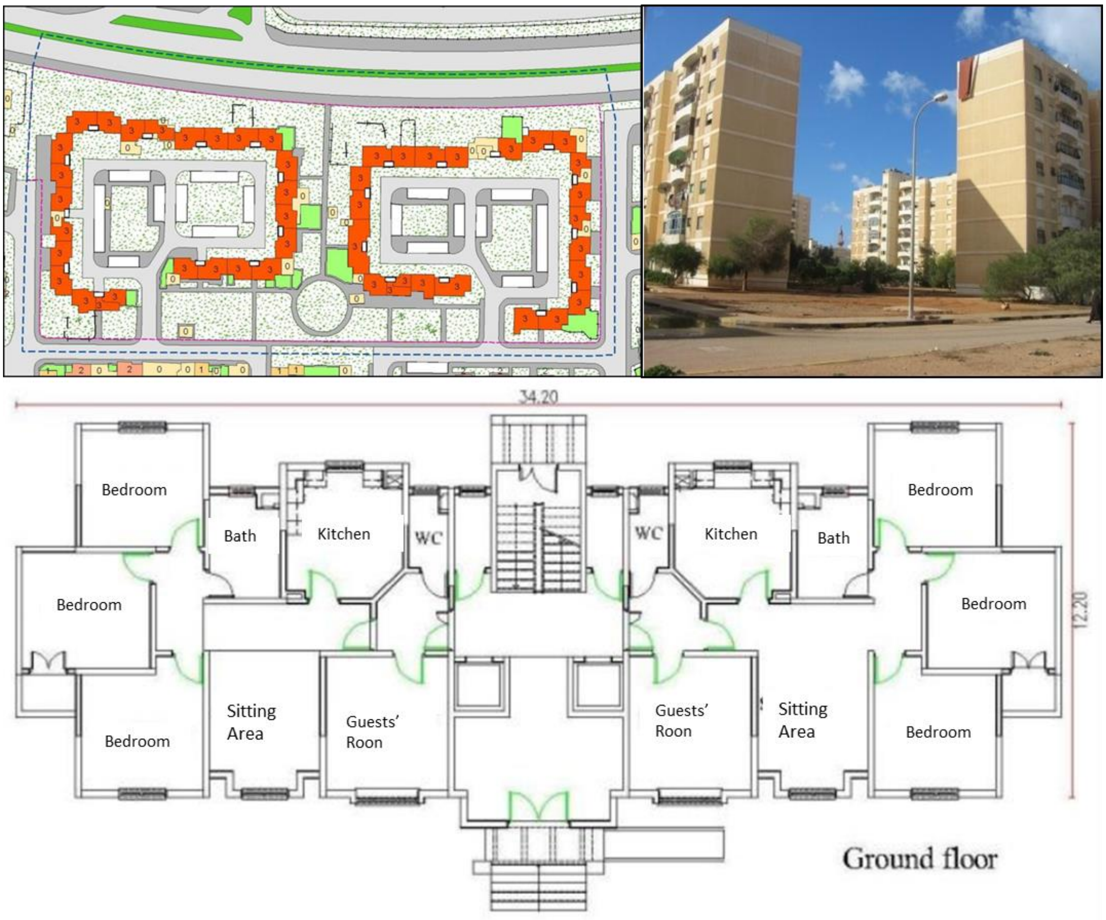


Figure 2. 13 Design layout of apartment type (UPA 2009; Mohamed 2013)

2.9 Chapter summary

This chapter offers a wider picture of the research context (Benghazi, Libya), its location and climate features, housing typology, dominant construction method, and materials. It provides a review of the energy consumption profile, building energy efficiency codes, legislation, and regulations, as well as discussing the potential and future prospects of solar energy in Libya.

Chapter 3: Literature Review

3.1 Introduction

This chapter provides a general review of relevant knowledge in the research field of building energy retrofits. It starts with an overview of essential understandings of building energy retrofitting, highlighting different energy retrofit measures for residential buildings in hot climates. It then reviews existing literature on residential building energy reduction in Libya, to identify areas where further study is required. However, due to the limited research on energy efficiency in the Libyan context, the search for articles was expanded to include the studies that were conducted on retrofitting residential buildings in neighbouring countries which are similar to Libya in terms of climate and construction materials.

3.2 Theoretical Background

3.2.1 Energy Retrofit Measures for Existing Residential Buildings in Hot Climates

Retrofitting refers to the implementation of modifications to existing buildings to lower their energy demand, save money, increase comfort, and reduce greenhouse gas emissions. A further benefit of retrofitting an existing building instead of constructing a new one is that the generation of associated wastes can be avoided, while embodied energy is conserved (Khairi et al. 2017). Moreover, retrofitting existing buildings is more cost-effective, and the construction timeframe may be faster than when constructing a new building, which takes a longer time to be completed (Khairi et al. 2017). Many studies suggest that retrofitting can provide better indoor environment quality for occupants, and especially in terms of and lighting, as well as providing the ability to control the temperature, which greatly affects comfort, mental health, and productivity (Iversen et al. 1986; Miller et al. 2009; Curl et al. 2015). Because existing residential buildings today account for the majority of the built environment, and most of these are to some extent old or employ dated energy source and storage methods, it is vital to begin energy conservation measures to enhance these buildings' performance through energy retrofitting (Paradis 2016; Mejjaouli and Alzahrani 2020). It is easier to construct an energy-efficient building from the ground up, while retrofitting existing buildings is a challenging task because of factors such as the risks associated with this, and a potential lack of information related to the physical conditions of the building.

There are two alternatives to building energy retrofits: the first is the deep retrofit, which is known as a 'whole-house retrofit'. This involves major change to the building's fabric and systems, whereas, in shallow retrofits, minimal upgrades to the building are made. Shallow retrofits can provide energy savings of 10–20%, and may be a more attractive option than deep energy retrofits for meeting short-term goals, while deep energy retrofits achieve long-term energy goals. However, simulations of building stock scenarios have indicated that allocating available annual funds to a large number of lower-cost shallow renovations rather than fewer, higher-cost deep energy renovations may result in unpredictable, permanent long-term consequences (Zhivov and Lohse 2020). Thus, to obtain future-proof efficiency levels, it is necessary to conduct deep retrofit measures (Blücher 2018). The need for energy in an existing building can be reduced by implementing passive and active energy efficiency measures, and by using renewable energy systems to offset residual building energy needs (Hayter and Kandt 2011) (Figure 3.1).

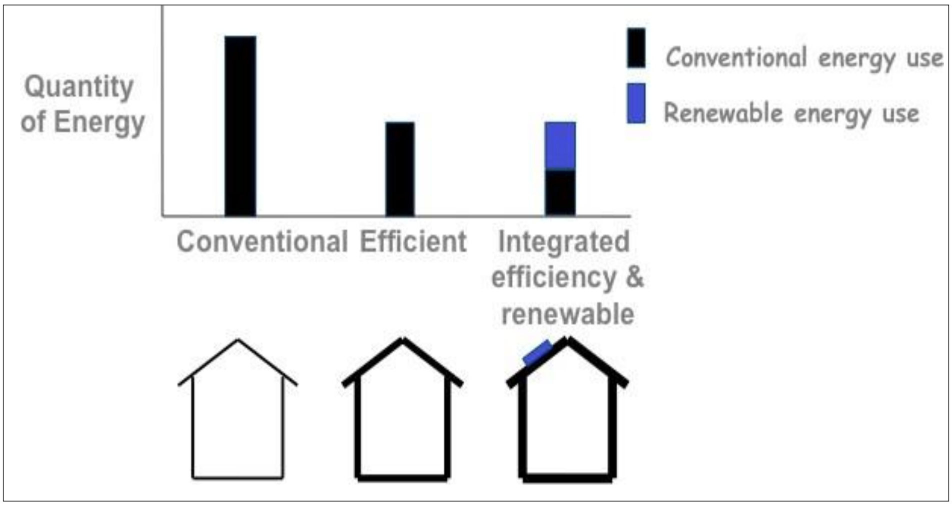


Figure 3. 1 Demonstration of how combining energy efficiency and renewable energy strategies reduces the need for conventional energy (Hayter and Kandt 2011)

From this understanding of building energy retrofitting in general, it is necessary to clarify the factors that affect the energy efficiency of residential buildings. Different factors in buildings, such as thermal mass, insulation, window size, orientation, and shading, can help to promote indoor comfort and energy use.

3.2.1.1 Building fabric

The ability of the building envelope to protect indoor spaces from heat loss or gain depends on several factors, including thermal mass, insulation, window characteristics (window-to-wall ratio, glazing material), and shading (De Silva and Sandanayake 2012).

3.2.1.1.1 Thermal Mass

The thermal mass of building materials is a crucial characteristic in minimising heat gain and loss. It has a significant influence on both energy consumption in buildings and indoor thermal quality (Ali 2018). Heavyweight building materials can store a great deal of heat, whereas lightweight building materials do not store significant heat, making the thermal mass of the building envelope low. Therefore, building construction materials are generally grouped into two main categories: low thermal mass materials; and high thermal mass materials. The term thermal mass is commonly used to refer to the ability of building construction materials to absorb heat, store it, delay heat transfer through a building component, and release it at a later time (Kalogirou et al. 2002) (Figure 3.2).

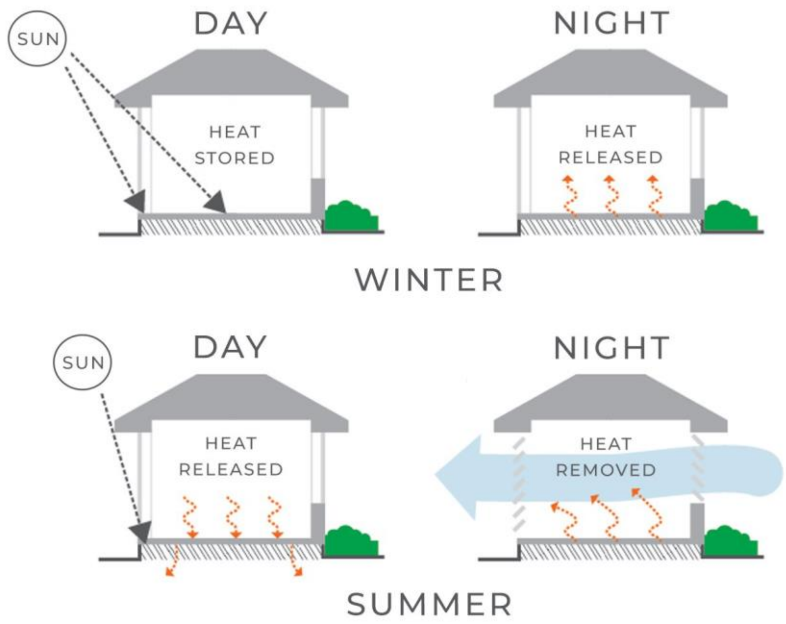


Figure 3. 2 The effect of thermal mass in summer and winter (ACarchitects 2019)

High thermal mass materials also contribute to delaying the time of peak load to a later time in the day. This leads to a decrease in energy demand during peak hours, and an increase in the efficiency of the air conditioning system (AC), as peak load would occur later in the evening when the outdoor air temperature is lower than in the afternoon (Al-Sanea and Zedan 2011). When the outside temperature is high, the thermal mass has a lower temperature, leading to greater absorbance and storage of heat, and keeping the internal temperature lower during the day. This stored heat is released at a later time to the internal spaces, leading to a slight increase in temperature. Nevertheless, the indoor temperature can stay within the comfort zone with cooling night effects (Almansuri 2010). High thermal mass materials such as mudbrick, which has low thermal conductivity, were commonly used in the vernacular architecture of Libya. On the other hand, construction materials used in contemporary housing stock Libya such as concrete blocks have higher thermal conductivity making them inefficient in terms of energy savings.

3.2.1.1.2 Wall Coating Characteristics (Colour and Texture)

Exterior wall coatings, which make up the outermost layer that is exposed to outdoor conditions, have an impact on a building's energy efficiency and thermal comfort level (Zhang et al. 2024). A study conducted by Chaiyosburana (2013) investigated the influence of building envelope colour on heat transfers and energy consumption. The study revealed that buildings coated with high solar reflective paint resulted in reducing the wall and roof surface temperature and room temperature by about 3-4° C when compared with conventional colour coated buildings (Chaiyosburana et al. 2013). Elie Tawil (2010) states that dark roofs absorb 90% or more of incoming solar energy, causing the roof to gain a temperature of up to 66° C in the hot season, resulting in increased heat flow into the building and more energy use for cooling. Light-coloured roofs, or cool roofs, on the other hand, reflect between 25 and 90% of solar radiation, bringing down the roof temperature and consequently reducing the need to operate air conditioners (Elie Tawil 2010). However, cool colours can exert a reverse effect in wintertime leading to an increased need for heating. Therefore, the paint's characteristics must be properly chosen in order to maintain a balance between limiting heat gain in the summer and allowing it in the winter. Due to the high intensity of solar radiation across the entirety of Libya, with an annual average of 3500 hours of sunlight (Alasali et al. 2023), cool coatings are more appropriate in this context (Suehrcke et al. 2008).

Other indicators of the amount of energy absorbed by a surface include the properties of the chemical substance that constitutes the surface, and the surface roughness, wherein each can modify solar absorptance, and the higher the surface roughness, the greater the solar absorptance (Dornelles et al. 2007).

3.2.1.1.3 Insulation materials

A significant amount of heat transmittance from the building's surrounding environment to its interior spaces can be caused by inefficiently insulated walls and windows. Inefficient insulation material has low resistance to conductive heat flow, which leads to an increase in the thermal transmittance factor (U-value). Heat conductivity, thickness, and density are the most important factors that influence the thermal transmittance of the insulation materials, in which the lower the U-value, the more efficient the insulation. For this reason, the absence of insulation materials from the components of the building envelope drives a considerable amount of heat to penetrate through it and thus leads to the consumption of a large amount of energy (Zhao et al. 2006). A well-insulated and sealed building envelope (wall and roof) with appropriately selected glazing is a preferential solution for increasing the suitability of the envelope's thermal characteristics, which results in minimising heating and cooling loads and maximising solar heat gain during the winter (Zhao et al. 2006). This is because the installation of thermal insulation to the building envelope provides a reduction in the U-value, which increases thermal resistance and subsequently reduces heat transfer. However, residential buildings in Libya have been constructed without any insulation in the envelopes, resulting in high energy usage (Ali 2018).

Biobased Insulation Materials

Bio-based insulation materials are insulation products made from renewable plant and animal fibers, providing a sustainable alternative to conventional insulating materials. Based on previous studies, biobased materials are durable, renewable, environmentally friendly, and have low relative density and strong thermal properties (Ryszard M et al. 2012; Mann et al. 2023). Also, in contrast to petroleum-based insulation materials, which contain chemical components and carry a potential risk of emitting pollutants and causing health issues (Wi et al. 2021), biobased insulation materials pose minimal or no risk to human health, causing no irritation to the eyes, skin, or lungs, and are capable of absorbing and releasing moisture without substantially affecting thermal performance (Korjenic et al. 2015). In Libya, there are various raw materials from which insulation materials can be produced locally, such as sheep’s wool, camel hair, and date palm fibres. Livestock have traditionally represented the largest income-producing item in agricultural production, with sheep constituting the largest percentage of livestock (Nelson 1979). Their number grew from 2.8 million head in 1977 to around 6 million head in 2011 (Mohamed and Abuarosha 2014). In addition, more than 80% of the world’s camel population is found in African countries, including Libya. There are a wide variety of camel breeds available in various locations in Libya, such as Fakhreya to the west of Benghazi, Tibisti in the southern areas of Libya, Kasabat in northwestern Libya, Oulad Bou Sayf in the western oasis of Libya, and Sirtawi, found mainly in the Sirt area in the mid-coastal zone in Libya (Wardeh 2004). Libya also has a long history of date palm farming, which has played an important role in livelihoods in the desert and semidesert areas (Battaglia et al. 2015). Date palm trees are currently grown in areas along the northern coast and the oasis in the south (Nelson 1979; Battaglia et al. 2015), and according to Ministry of Agriculture data, Libya has about ten million palm trees distributed across its territory, concentrated especially in the regions of AlJufra, Jalo, and Awjila. Hence, the potential for generating adequate insulating materials in Libya is promising because of the availability of these raw resources.

The Properties of Biobased Insulation Materials

When selecting insulating materials, the thermal properties of the materials, such as thermal conductivity, thermal effusivity, thermal diffusivity, heat capacity, and density, are extremely important to consider. However, thermal conductivity is the most important property of insulation material, as it represents the capacity to resist heat and, hence, to insulate (Cosentino et al. 2023). Biobased insulation materials possess low thermal conductivity, like many convention insulation materials (Cascione et al. 2022). For instance, sheep's wool has a thermal conductivity of 0.039 W/mK making it similar to mineral wool insulation material.

In addition to their good thermal conductivity values, biobased insulation materials such as wood fibreboard, flax fibres, hemp fibres, jute fibres, and sheep's wool have a high moisture management capacity. This means that a wall with biobased insulation materials can maintain its thermal performance without the need for the water vapour barriers which many conventional insulation materials need (Jerman et al. 2019).

The Environmental Impact of Biobased Materials

As buildings become more energy-efficient during their operating phase, the effect of their embodied energy becomes more prominent (Brás 2016; Ajayi et al. 2019). Embodied carbon of construction refers to the carbon dioxide emissions associated with materials extraction and manufacturing, transport of the materials to site, building construction, materials replacement, and end of life disposal (Hammond et al. 2011; Waldman et al. 2020). About 40% of energy-related CO_2 emissions are attributed to the building and construction sector (Hammond et al. 2011; Abergel et al. 2017; Min et al. 2022), and up to half of these are embodied CO_2 emissions (Hammond et al. 2011; Waldman et al. 2020). Consequently, to mitigate climate change, not only do energy consumption and related greenhouse gas emissions during buildings' operating phase need to be reduced, but also their whole life cycles should be considered (Röck et al. 2020). Reducing embodied carbon requires exchanging carbon intensive materials such as are mostly used for envelope insulation with lower carbon equivalents. The use of biobased materials offers promising alternatives which require less energy to manufacture, and store carbon during growth, leading to embodied carbon reductions (Galimshina et al. 2022). The potential benefits of such materials are identified by a life cycle assessment which determines the embodied carbon of biobased products by analysing the overall GHG emissions produced throughout their life cycle. This includes assessing emissions from raw material extraction, manufacturing, transportation, use, and disposal, all expressed in carbon dioxide equivalent (CO_2e) units.

Biobased insulation materials have lower embodied carbon than fossil fuel-derived options. For instance, the embodied carbon for extruded polystyrene and aerogel reach 3.5 kg CO_2e and 18.7 kg CO_2e respectively (Grazieschi et al. 2021), while for biobased materials such as hemp fibres, the embodied carbon reaches only 1.4 kg of CO_2e (de Beus et al. 2019). Hence, usage of bio-based insulation materials can offer an alternative which can decrease emissions in comparison with fossil fuel-derived options.

3.2.1.1.4 Orientation

A consideration of the direction of openings, walls and roof in relation to the movement of the sun around a building is essential for reducing heat gain. The exposure of the walls and roof to the sun depends on their orientation. For instance, exposure to the sun of vertical surfaces such as walls differs from the exposure of horizontal or inclined surfaces such as the roof. The more the surfaces are exposed to the sun, the more solar radiation strikes the surface. Baruch (1998) reports that in summer, the roof, western and eastern walls are exposed to a higher intensity of solar radiation compared with the southern walls (in the northern hemisphere), which are exposed to a lower intensity (Baruch 1998). In winter, the opposite process occurs, and in this season, the southern walls are exposed to higher levels of solar radiation. This means that the eastern and western façades are more exposed to extreme sunlight in the summer. This must be avoided because it leads to greater radiation absorption and a rise in interior temperatures. Therefore, the solution lies in reducing the area of these surfaces as much as possible, while raising the area of the southern surface because of its lesser exposure to summer radiation and greater exposure to the needed winter radiation.

3.2.1.1.5 Window glazing

There is no doubt that the larger the windows, the higher the level of radiation enters the interior spaces, raising the indoor temperature. As a result, the size of these openings should be as small as possible to reduce the proportion of heat gain. However, a study by Sing et al. (2021) reveal that despite the fact that the area of glazed windows should be relatively small, heat gain or loss through them can be significant due to their high thermal conductivity.

The thermal resistance properties of windows are governed by four factors within the window system, namely: the materials and detailing of the window frame; treatment of the glazing material and surface area; the number of air spaces between glazing layers; and the gas that fills the airspaces (Baruch 1998). Many kinds of glass have been developed which can be differentiated by these factors. The least desirable types in terms of thermal resistance include single clear glass, as commonly used in Libyan housing, and which permits the highest amount of solar radiation to pass through and consequently increases heat gain. By contrast, super insulating glass with three glazing layers and spaces filled with insulation gas has a lower conductivity and lower heat gain. In addition, insulated window panels, window films, and low emissivity (Low-e) windows can also contribute to reducing infrared (IR) heat flow into buildings, ensuring that the desired degree of thermal comfort is achieved without consuming additional energy from heaters or air conditioners (Khairi et al. 2017).

A study by Marino et al. (2017) aimed to find the optimal size of window to allow for the least amount of total energy consumption while allowing comfort conditions for most of the year in the context of Italian building stock. The research analysis was carried out using EnergyPlus simulation software, and window dimensions were assessed in terms of the window to wall ratio (WWR). The study illustrates that the lower the WWR, the lower the cooling loads, while lighting energy demand increases due to the lower visible transmittance value (Figure 3.3). The study also revealed that the overall primary energy demand (heating, cooling, and lighting) is kept to a minimum when the WWR is between 35% and 45%, regardless of orientation, the building surface area-over-volume ratio, or the efficiency of the HVAC system. Moreover, if energy consumption is to be kept within a specified level, a more insulated envelope allows for a slight increase in window sizes (Marino et al. 2017).

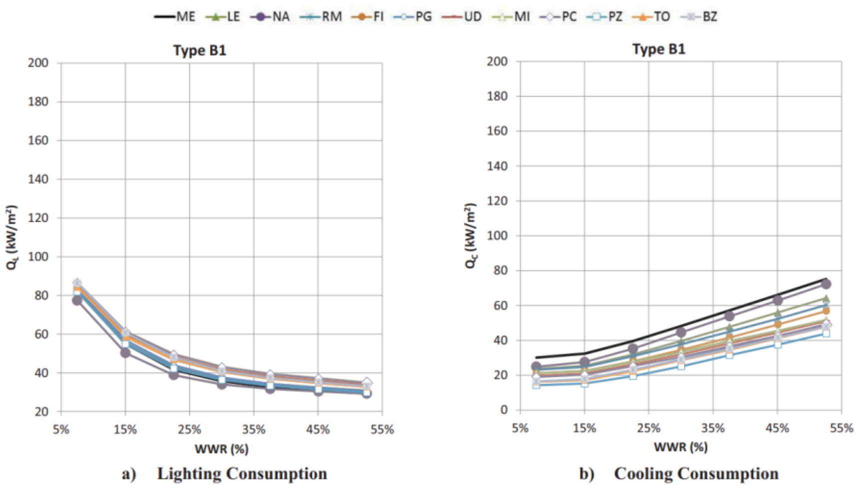


Figure 3. 3 Primary energy consumption versus WWR (Marino et al. 2017)

The heating and cooling loads of a building are also affected by the combination of U-value, solar heat gain coefficient (SHGC), and window-wall ratio (WWR) (Ahn et al. 2016; Macé de Gastines and Pattini 2020). A study by Ahn et al. (2016) investigates the influence of both thermal transmittances (U-value) and SHGC of windows with different window-wall ratios. The findings reveal that in the case of low WWR, both U-value and SHGC have a slight influence on energy consumption (Ahn et al. 2016).

3.2.1.1.6 Shading

The shading of the building and windows, as well as of outdoor spaces, reduces summer heat, saves energy, and provides comfort, in which up to 90% of solar radiation can be blocked by shading (Gireia et al. 2012). This shade can be provided by buildings themselves, wherein each building throws shade onto the building next to it, or by vegetation. In cooling-dominated regions, window shadings result in significant energy savings and comfortable indoor thermal conditions. Shading can be installed internally or externally, be fixed or moveable, and be manually or automatically operated (Meek and

Brennan 2011; Ghosh and Neogi 2018). Solar radiation can be blocked by external shadings before it penetrates the building's interior. However, if shadings are internally installed, the solar radiation is absorbed and then re-radiated to the inside, leading the cooling load to increase (Ghosh and Neogi 2018). In addition, movable shading devices are considered more efficient than fixed ones, since they can be adjusted to block direct solar radiation in the summer and allow it throughout the winter. Manually operated movable shading systems, on the other hand, are highly dependent on occupant behaviour, privacy considerations, and emotional state, and may result in inadequate control behaviour if control involves complex or too frequent adjustment (Yao 2014; Ghosh and Neogi 2018). As a result, it is important to improve occupant behaviour with shading devices to enable them to respond effectively to outdoor conditions, and particularly solar radiation (Meek and Brennan 2011). Simple manual or automated control approaches to operating shading devices, with only two shade adjustments at a fixed time every day (on arrival and departure), as shown in Table 3.1, can achieve comfortable indoor conditions and better energy performance without interrupting access to daylight (Yao 2014) .

Table 3. 1 Automated and manual solar shading control strategy (Yao 2014)

Season	Time	Shading sate	The aim of the control
Summer	Daytime	Shade 2/3 of window area	Block excessive solar gain and keep enough daylight
	Nighttime	Fully open	Enable natural ventilation to decrease indoor temperature
Transition	All time	Shade 1/2 of window area	Try to get a balance between solar radiation and daylight
Winter	Daytime	Fully open	Admit solar heat to warm indoor space
	Nighttime	Fully closed	Reduce heat loss

3.2.1.2 Building services and systems

3.2.1.2.1 Heating, cooling and mechanical systems

Building systems such as HVAC and electrical systems can have a huge impact on energy usage patterns. For example, the air-conditioning system, or space cooling system, is regarded as the most energy-consuming equipment in residential buildings (Sing et al. 2021). HVAC systems and their related energy consumption have become an indispensable asset for providing thermal comfort, accounting for nearly half of the energy used in buildings (Pérez-Lombard et al. 2008; Afram and Janabi-Sharifi 2014). In addition, the demand for air conditioning is set to gradually rise over coming decades, as ambient temperature levels are expected to increase, which will inevitably lead to increased energy consumption. Thus, these challenges highlight the importance of creating a green and sustainable system that reduces human impacts on natural environments by reducing demand for energy (Narayanan 2017).

The heating and cooling efficiency of air conditioners can be described by the terms COP (coefficient of performance) and EER (energy efficiency ratio), in which, the higher the COP and EER, the higher the efficiency of the cooling system. A study by Rakhshan and Friess (Rakhshan and Friess 2017) was carried out on an existing reinforced concrete villa located in Dubai. The researchers upgraded the existing air conditioning system, which had a COP of 1.80, to a COP of 2.78. The simulation results showed a reduction of approximately 31% in energy usage. On this basis, therefore, proper service and system selection is critical for making energy savings while guaranteeing comfort for the building's occupants (De Silva and Sandanayake 2012). However, without a well-insulated and sealed building envelope, HVAC system cannot work efficiently (Al-Sanea and Zedan 2011). Insulating the building envelope can effectively decrease the peak load of the cooling system (Fadzil et al. 2017).

3.2.1.2.2 Lighting System

In residential buildings, artificial lighting consumes a substantial amount of electricity. In addition, it generates heat along with other equipment, leading to an increase in energy demand related to the building's cooling system. Harish and Kumar (2016) argue that lighting systems not only account for a particular share of the building's energy consumption, but also act as a space load, as they dissipate appreciable heat during their operation (Harish and Kumar 2016). Incandescent lightbulbs are commonly used in existing residential buildings which are not energy efficient. However, replacing the existing lighting type with LED lighting or low-energy lamps such as fluorescent lamps can have a substantial influence on the energy consumption of both lighting and cooling (Sing et al. 2021).

3.2.1.3 Renewable energy system

Renewable energy sources (RES) such as photovoltaic energy generation system, solar thermal energy (Solar hot water), geothermal heat pumps, wind turbines, and biomass systems can be integrated with building energy systems to help reduce energy demand (Hayter and Kandt 2011; Jenkins et al. 2019). However, selecting the appropriate renewable energy technology depends primarily on the availability of the renewable energy resource at or near the building site (Tawil et al. 2018). Solar energy is the most affordable source of energy because of its availability and low cost compared to other renewable sources (Devabhaktuni et al. 2013; Kannan and Vakeesan 2016). Libya has one of the highest levels of solar irradiation in the world, making it one of the best locations for PV technology.

3.2.1.4 Adjusting occupants' behaviour

Social and cultural values play an important role in guiding and directing people's behaviour in both internal and exterior environments in Muslim countries such as Libya (Almansuri 2010). Occupants spend most of their time inside buildings, which leads to greater use of electrical appliances and lighting operations. Energy-efficient technology and occupant behaviour have traditionally been treated as independent actors (Moezzi and Lutzenhiser 2010). However, recent studies have argued that the fundamental cause of discrepancies between actual and predicted energy consumption may be the separation between these two areas in building energy efficiency strategies (Ortiz et al. 2017). Accordingly, for more accurate measurement of energy consumption, occupants' behaviour (occupancy pattern, attitude and beliefs) should be considered in the process (Ortiz et al. 2017).

Occupant behaviour is an important factor influencing actual building energy use. How people interact with a building is important to consider, in which, giving the opportunity to the occupant to control their interactions with the systems in buildings increases their satisfaction (Tam et al. 2018). So, it is critical to understand the way in which people interact with a building and how this affects the overall efficiency of that building in terms of energy consumption (Tam et al. 2018; Zhang et al. 2018), as inadequate consideration of user behaviour when retrofitting buildings may result in the selection of inappropriate energy-efficient measures (Pan et al. 2017). Human behaviour in buildings is influenced by a wide range of internal and external factors that drive people to interact with the building and its systems in a particular way (Barthelmes et al. 2017; Paone and Bacher 2018). According to (Stazi et al. 2017; Tam et al. 2018), these factors may be caused by objective factors like environment, air velocity, temperature, noise, accessibility to monitor building features, time, and activity type, as well as subjective factors like comfort perceptions, desires, gender, age, values, and social interaction. External influences such as politics, economics, and culture also influence these variables. Figure 3.4 shows the main factors influencing occupant behaviour.

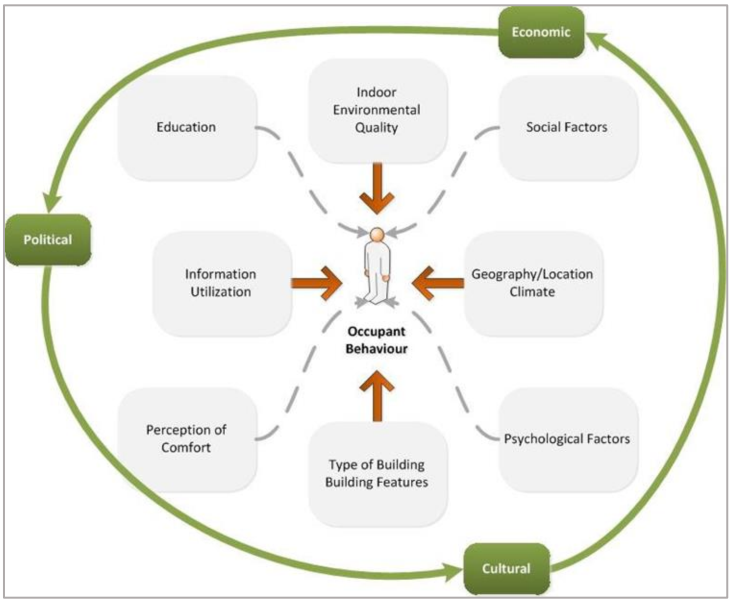


Figure 3. 4 Influential factors for occupant behaviour (Tam et al. 2018)

Over recent years, various energy codes have emerged within energy-efficient design strategies with a view to achieving a nearly zero energy target. However, the effectiveness of these strategies is highly reliant on how the building's inhabitants interact with them, or more specifically, on the energy-related lifestyles they adopt (Barthelmes et al. 2017). The way inhabitants interact with the building service systems, such as cooling, heating, ventilation and lighting systems, and even behaviours related to window opening and use of shading, can be effectively used in energy use reduction. For example, (Barthelmes et al. (Barthelmes et al. 2017) argue that raising occupant awareness in homes has the potential to lead to energy savings of up to 18%, while Zhang et al. (Zhang et al. 2018) state that the energy-saving potential of occupant behaviour is estimated to be between 10% and 25% in residential buildings. The set-point temperature, which is highly dependent on occupant behaviour, can have a substantial impact on a building's cooling and heating load (Wang et al. 2015).

Zhang et al. (Zhang et al. 2018) argue that occupant lighting behaviour is influenced by occupancy, time of day, and occupant movement inside the building. Although building occupants who seek daylight rather than depending on artificial lighting can achieve a significant energy saving. Automated lighting control combined with manual control can also achieve annual reductions in lighting loads reaching 98% (Bourgeois et al. 2006). Moreover, a sequence of experiments examined intelligent sensors, such as an infrared occupancy sensor, CO_2 sensor, lighting and ventilation sensors, and researchers concluded that these sensors showed energy-saving potential. For example, intelligent lighting occupancy sensors could save up to 30% of the electricity used for lighting (Garg and Bansal 2000).

On the other hand, other studies conducted on the influence of occupant behaviour on building energy performance reveal that user behaviour has no tangible effect. For instance, Buso et al. (Buso et al. 2015) investigated the effect of occupant behaviour in terms of window opening and use of shading in various building envelope designs, using a dynamic building energy simulation tool (IDA ICE). It was discovered that through raising thermal mass and reducing the transparent area of the envelope, a situation could be reached in which energy efficiency was not influenced by variability in occupant behaviour. This means that building envelope features (walls and openings) play an important role in modifying the energy efficiency of the building as well as the effects of occupant behaviour. Furthermore, due to a lack of realistic behavioural patterns to drive simulations, occupant behaviour adjustment does not receive significant attention. The impact of behavioural changes is typically demonstrated using assumed patterns, which could overstate or underestimate the energy-saving potential (Pan et al. 2017).

Several research studies have been conducted to evaluate the benefits of energy retrofit strategies for existing residential buildings. The following four areas are the most widely considered in residential building energy retrofitting:

1- Building fabric.
2- Building services and systems

3- Renewable energy systems.

4- Occupant behaviour.

3.2.2 Thermal comfort

Thermal balance or thermal comfort refers to the situation where human beings feel satisfied with the temperature of their surrounding environment. It is defined by ASHRAE Standard 55 (ASHRAE55 2017) as the state of mind that expresses satisfaction with the surrounding environment.

Macpherson, in 1962, determined six factors affecting thermal sensation: four physical factors (air temperature, air velocity, relative humidity, mean radiant temperature); and two personal factors (clothing insulation and activity level)(Macpherson 1962).

The mean radiant temperature is a significant factor affecting indoor thermal comfort in buildings whose envelopes are exposed to intense solar radiation (Atmaca et al. 2007). However, in the case of buildings with inefficient fabrics with a high U-value, the high temperature of the surrounding air contributes to a rise in the temperature of the building's envelope. This results in a corresponding increase in mean radiant temperature and indoor air temperature, leading the occupants to feel discomfort. Therefore, the building fabric needs to be well insulated and airtight to prevent heat gain in summer and heat loss in winter and to achieve a more stable and comfortable indoor environment (Passivhaus 2024).

There are two different approaches developed to predict thermal comfort: the rational or heat-balance approach; and the adaptive approach. The rational approach, characterised by Fanger's work, uses data from climate chamber experiments to support its theory, whereas the adaptive approach uses data from field studies of people in buildings (Djongyang et al. 2010).

3.2.2.1 The heat-balance approach

The heat-balance approach is based on Fanger's experiments, which predict the mean response of a large group of participants according to the ASHRAE Standard 55 seven-point scale of thermal sensation, ranging from cold (3) to hot (+3), with neutral (0) in the middle, as follows: cold -3, cool - 2, slightly cool -1, neutral 0, slightly warm 1, warm 2, and hot 3 (ASHRAE55 2017). This seven-point scale became known as the Predicted Mean Vote index (PMV). The PMV was then incorporated into the Predicted Percentage of Dissatisfied index (PPD), for the evaluation of indoor thermal environments in buildings (Djongyang et al. 2010). On the ASHRAE 55 seven-point scale, a positive PMV value indicates that the temperature is above the ideal level, while a negative value indicates that the temperature is below the ideal comfortable condition (Yau and Chew 2014). Zero PMV is the ideal thermal comfort level, while the acceptable PPD range for thermal comfort in buildings is set by

ASHRAE 55 at 10% dissatisfaction. The PPD curve corresponds to 10% discontent for PMV of -0.5 and +0.5. The relationship between PMV and PPD is shown in Figure 3.5.

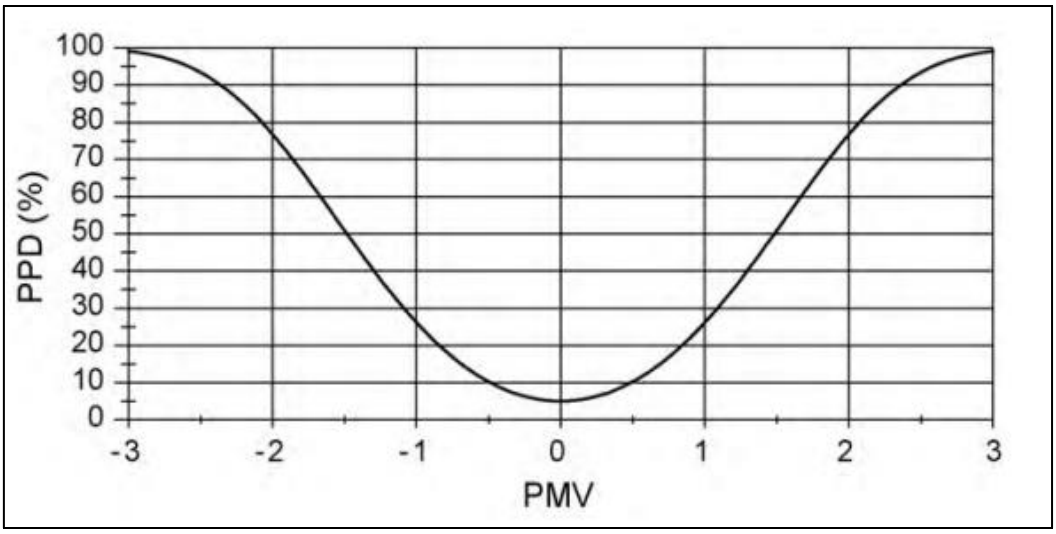


Figure 3. 5 Relationship of PMV to PPD (ASHRAE55 2017)

3.2.2.2 Adaptive approach

Because the Predicted Mean Vote index does not consider contextual, social, and cultural factors when predicting thermal comfort, an alternative comfort approach known as the adaptive approach later emerged. The adaptive approach was developed from field observations with the aim of studying the actual acceptability of the thermal environment, which is greatly influenced by the context, occupant behaviour, and individual thermal expectations (Djongyang et al. 2010). People may adapt their behaviour to alter their body's heat balance and attain thermal comfort. Behavioural adjustment can be divided into three categories: personal adjustment, technological adjustment, and cultural adjustment. Personal adjustment includes changing activity, clothing, or moving to other places. Opening or closing windows and turning air conditioners on and off are examples of technological adjustment. Cultural adjustments include taking a break on a hot day or arranging activities in line with the temperature (Yau and Chew 2014).

Although the importance of adaptive comfort has been established by numerous studies since the early 1970s, it was first formalised into a thermal comfort standard in the form of the ASHRAE Standard 55 in 2004 (Rawal et al. 2022). The standard determines limits of thermal conditions in naturally ventilated buildings. As shown in Figure 3.6, this standard determines limits of thermal conditions. Two acceptability limits (90% and 80%) are defined (ASHRAE55 2017). The following equations correspond to the acceptable operative temperature ranges in Figure 3.6

Upper 80% acceptability limit (°C) = 0.31 t mean temp(out) + 21.3 (1)

Lower 80% acceptability limit (°C) = 0.31 t mean temp(out) + 14.3 (2)

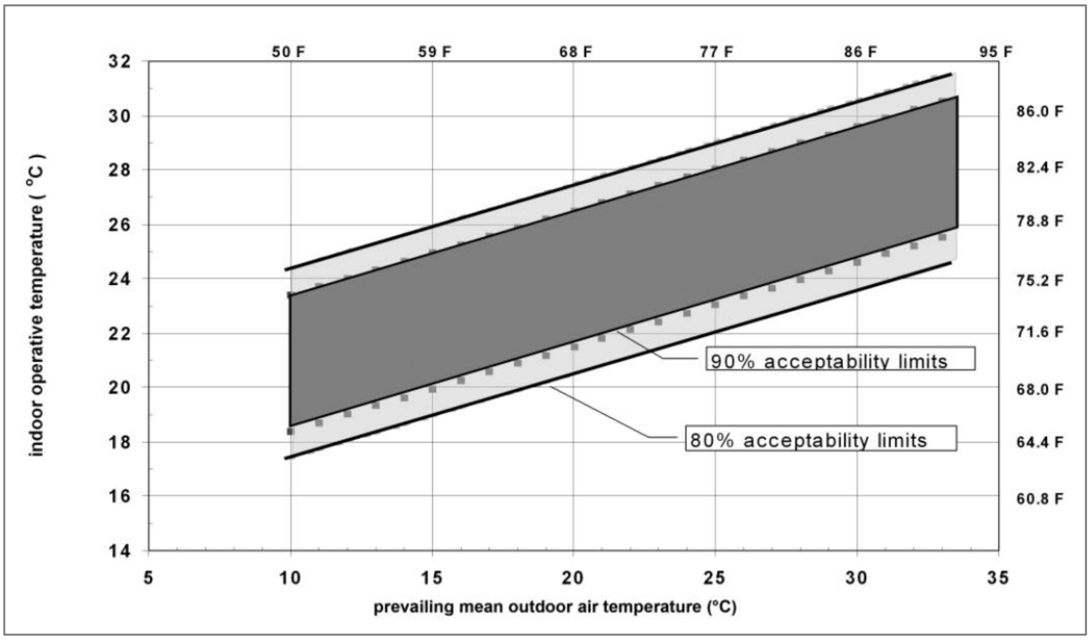


Figure 3. 6 Acceptable operative temperature ranges for naturally conditioned spaces (ASHRAE55 2017)

3.2.3 Energy efficient building standards (Passivhaus standard)

The Passivhaus Standard is a building standard seeking to achieve housing that is energy efficient, comfortable and affordable at the same time (Passivhaus 2024). Under the International Passive House Association's standard, the primary energy demand limit for a Passivhaus is 120 kWh/m^2/y. The Passivhaus Standard also has other requirements, including that primary heating and cooling demand must not exceed 15 kWh/m^2/y, and indoor thermal discomfort hours should not exceed 10% of the year. Each of these criteria are achieved through the implementation of the five Passivhaus principles:

- Thermal insulation
  All opaque building components of the exterior envelope of the house must be very well insulated, with a U-value of 0.15 W/(m^{2}K) at the most.
- Windows
  The window frames must be well insulated and fitted with low-e glazing filled with argon or krypton to prevent heat transfer. this means a U-value of 0.80 W/(m^{2}K) or less, with g-values of around 50%.
- Airtightness of the building
  A maximum of 0.6 air changes per hour (ACH) at 50 Pascals pressure (ACH50) is permitted.

- Absence of thermal bridges

Thermal bridges which cannot be avoided must be minimised as far as possible. All edges, corners, connections and penetrations must be planned and executed with great care.

- Ventilation heat recovery
  Efficient heat recovery ventilation is key, allowing for good indoor air quality and saving energy. In the Passivhaus, at least 75% of heat from exhaust air is transferred to the fresh air again by means of a heat exchanger.

Because meeting the Passivhaus target in older buildings is not always feasible, Passivhaus retrofit standards (EnerPHit) can be used. This slightly modified version allows for somewhat more generous standards which are more realistic to achieve in retrofits. It allows primary energy demand of up to 135 kWh/m^2/y, with primary heating and cooling demand of up to 30 kWh/m^2/y (Passivhaus 2021).

3.3 A Systematic literature review

The study aims to identify the optimal solutions for retrofitting existing residential buildings stock in Libya. However, due to the lack of published articles for the Libyan context, The Author reviewed the relevant literature focusing on energy retrofit in residential buildings in Libya and neighbouring countries with similar climate features to Libya including Mediterranean and semi-arid climates as well as the PhD thesis on the energy efficiency of the residential building in Libya. This stage addresses the gaps in knowledge and emphasises the importance of current research and its potential contributions.

3.3.1 Objectives of the literature review

This review aims to identify the most widely addressed energy efficiency measures for retrofitting existing residential buildings in Libyan and neighbouring Mediterranean countries, and to identify the research methods and tools adopted in the process. Understanding the current state of energy efficiency in existing residential buildings in Mediterranean countries will help identify potential areas of intervention to improve the energy efficiency of existing residential stock in Libya. Figure 3.7 shows the location of Libya and neighbouring Mediterranean countries included in the review.

Figure 3. 7 The locations of Libya and neighbouring Mediterranean countries included in this review. Adopted from (WikimediaCommons 2024)

3.3.2 Materials and Methods

To explore energy retrofit measures in residential buildings, and to determine the corresponding research methods and tools adopted, the authors have decided to undertake a systematic review. This method of reviewing the literature is appropriate to provide a critical overview of previous studies and assess their quality, as well as to identify gaps in existing knowledge. This review therefore accomplishes its aims by following the search strategy and flow diagram for the preferred reporting items for systematic reviews and meta-analyses (PRISMA), developed by the Centre for Reviews and Dissemination to help authors improve the reporting of systematic reviews (Moher et al. 2009). However, this review does not fully follow the PRISMA method but rather certain aspects of PRISMA.

To obtain a preliminary data set, a protocol comprising the inclusion criteria and analysis method are developed. Major research engines including Scopus, ScienceDirect, and Google Scholar are employed to search for published articles on energy efficiency in residential buildings in Mediterranean countries including Libya. The Electronic Theses Online Service (EThOS) that is provided by the British Library is also searched.

3.3.2.1 Inclusion and Exclusion Criteria.

Inclusion and exclusion criteria are used to remove irrelevant articles, to include articles with a primary focus on residential buildings retrofit that are published in the most recent years. The review includes only English manuscripts; research work on Libya and surrounding Mediterranean countries; and work presented in conferences and academic journal publications, including journals focusing on empirical work, and building performance simulation. Due to the limited research papers on the Libyan context, PhD and master's theses on the Libyan context are included in the review. In addition, there are no previous studies on the research topic written in Arabic. Therefore, only English manuscripts are included in this study.

For literature search, the Scopus search engine is employed first, using specific search terms to search the titles, abstracts, and keywords of published papers. ScienceDirect, Google Scholar, and EThOS are then also used, with the same search terms, to search for additional studies not found in the Scopus search. The search terms chosen are: TI-TLE-ABS-KEY((residential) AND (building*) AND (energy efficiency) AND (Libya)); TITLE-ABS-KEY((residential)AND(building*) AND (retrofit* OR renovation) AND (Libya)); TITLE-ABS-KEY ((residential) AND (building*) AND (retrofit* OR renovation) AND (Mediterranean)); (Zero) AND (energy) AND (residential) AND (building*) AND (retrofit OR renovation) AND (Libya)) TITLE-ABS-KEY ((Zero) AND (energy) AND (residential) AND (building*) AND (retrofit OR renovation) AND (Mediterranean)).

The search results from Scopus are exported and the abstracts are screened to exclude irrelevant articles. Those articles from other research engines whose focus is not within the subject area, or which do not meet the inclusion criteria are also excluded. In the next step, the full text of all remaining articles found in all databases are assessed. Articles meeting the eligibility criteria are selected for the review. Lastly, the author carefully reviewed all the included papers to extract specific themes to analysis the papers. The review identified 50 publications of high relevance to the subject area. The results of the review are grouped into two sections: the first section presents a description of the four research themes identified from the reviewed studies; and the second section is devoted to content analysis based on those themes. Finally, the systematic review concludes with a discussion of the content analysis and ends by identifying knowledge gaps.

3.3.2.2 Parameters for Analysis of The Literature

The review analyses each study based on four research themes identified in this review: a) Types of energy retrofit measures; b) building energy modelling for building retrofit; c) energy model calibration for building energy retrofits; and d) optimisation methods.

a) Type of Energy Retrofit Measure

Energy use in residential buildings can be significantly reduced through the implementation of energy-efficiency measures or ERMs (Stieß and Dunkelberg 2013). These measures are broadly classified into the following three main categories: energy conservation, energy generation and energy management (Ma et al. 2012) (Figure 3.8). Retrofit measures for energy conservation include optimising the building envelope through passive measures such as adding insulation materials, using an efficient window glazing system as well as using energy efficient systems as active measures. Retrofit measures for energy generation include the use of renewable energy such as solar photovoltaics (PV) systems. Retrofit measures for energy management involves consideration of residents' behaviours regarding use of lighting and equipment, adjusting set point temperatures, in addition to using smart energy systems. Energy- efficiency measures can be implemented individually (single measures), or for more energy saving potential can be employed in combination (combined measures) (Marshall et al. 2016).

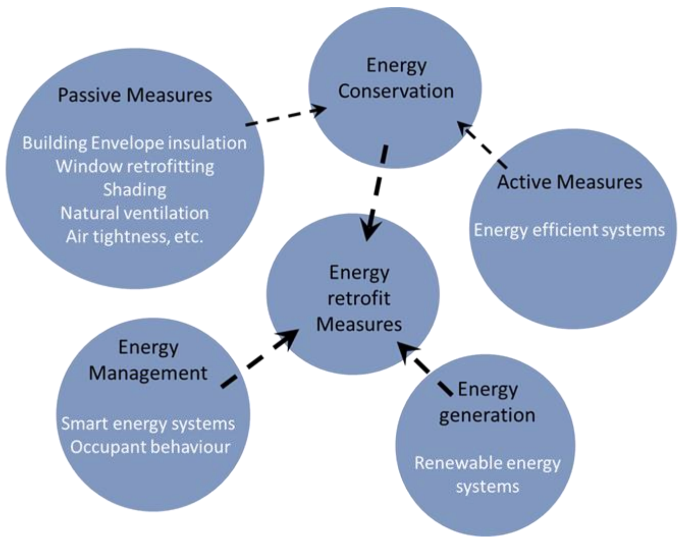


Figure 3. 8 Main categories of building retrofit measures adopted from (Ma et al. 2012)

b) Building Energy Modelling for Building Retrofit

Building energy modelling is an interdisciplinary field that incorporates concepts and research from electrical and electronics engineering, civil engineering, mechanical engineering, and architecture (Harish and Kumar 2016). It can also be utilised to identify the possible sources and uses of energy in the existing buildings and to determine the best options for energy conservation measures (Gao et al. 2019). Energy modelling and simulations, which reveal the energy-saving potentials of any energy-saving strategy, are valuable tools in retrofit design (Aksamija 2015).

There are many building simulation software packages available currently for whole building energy performance simulation, with different levels of complexity and response to different variables. These packages include BLAST, DOE 2, eQUEST, TRNSYS, EnergyPlus, Energy Express, EFEN, ESP-r, IDA ICE, IES, Revit and others (Harish and Kumar 2016; Kazaryan et al. 2020). Building energy modelling uses three approaches, including: standalone energy simulation tools such as EnergyPlus; integration of energy modelling software with 3D modelling software, such as Revit; and all-in-one software such as DesignBuilder. However, in many studies, energy Plus is considered the most complete simulation software tool (Chowdhury et al. 2007; Sousa 2012; Alam et al. 2014; Muslim 2021). Muslim (Muslim 2021) conducted a review on simulation tools for building energy. The review reveals that EnergyPlus is preferred choice for building energy simulation because of its powerful capabilities, multi-platform integration and extensive validation of its simulation algorithm. Nguyen et al. (Nguyen et al. 2014) argue that EnergyPlus demonstrates a high level of reliability in predicting building energy performance.

c) Energy Model Calibration for Building Energy Retrofits

Building energy modelling is proposed as an efficient approach to predict the thermal performance of buildings, and as a procedure that assists building designers in evaluating the energy performance of a building and as a response, making necessary design changes (Aksamija 2015; Harish and Kumar 2016; Gao et al. 2019). Nonetheless, there is growing concern about the reliability of energy simulation models (Chong et al. 2021) . Li et al. (Li et al. 2015) argue that there is empirical evidence of noticeable discrepancies between actual and simulated building energy performance. The mismatch between actual and simulated (predicted) building energy performance is referred to as the 'performance gap'. This can be attributed to the assumptions made during the planning phase of energy retrofitting in existing buildings due to limited access to data, affecting the validity and dependability of energy models by these assumptions (Ma et al. 2012). Chong et al. (Chong et al. 2021) argue that the performance gap between measured and simulated building energy model has become increasingly evident with the adoption of smart energy meters and the Internet of Things (IoT). Therefore, to narrow the performance gap and to ensure the reliability of the simulation results, building model calibration is useful. Model calibration has become an essential step in building simulation to ensure agreement between actual and simulated building energy performance, to achieve reliable results and to allow simulation estimates to more closely match actual building performance (Mustafaraj et al. 2014; Monetti et al. 2015; Duverge et al. 2018; Goldwasser et al. 2018). This can be achieved by matching simulation outputs with field investigation measurements using energy meters and monitoring sensors. For model calibration, both real energy consumption and zone temperature are monitored in different studies for comparison with simulation results, to ensure the simulated building models closely match the actual building, and to enhance the accuracy of the building's simulation and optimisation (Penna et al. 2015; Royapoor and Roskilly 2015; Cornaro et al. 2019). As part of a research project (rp-1051) initiated by ASHRAE in 2005, Reddy et al. (Reddy et al. 2007) categorises building energy simulation calibration methodologies from existing literature into four groups as follows:

- Calibration based on manual iteration: a technique which involves the adjustment of inputs based on the user's experience until the program output matches the expected data.

- Calibration based on graphical techniques: in this calibration process, certain graphical representations and comparative displays of the results to orient the calibration.

- Calibration based on specific tests and analytical procedures: this method is based on measurement tests such as blower door tests or wall thermal transmittance (U-value). This calibration process is carried out without the use of statistical or mathematical methods.

- Automated methods of calibration which are based on analytical and mathematical approaches: this method is not user driven and relies on an automated process.

The ASHRAE 14 Guidelines assign two statistical indices to evaluate calibration accuracy: normalised mean bias error (NMBE) and coefficient of variation of the root mean squared error (CV(RMSE)) (ASHRAE14 2002). These errors should be within ±10% and ±30% respectively on an hourly basis or ±5% and ±15% respectively with monthly data. If the discrepancy between measured and simulated results falls within the acceptable ranges as defined by the ASHRAE 14 Guidelines, the model building is considered a calibrated model (Fernandez Bandera and Ramos Ruiz 2017) .Otherwise, the source of the discrepancy should be detected and altered until the simulated building results match the measured ones. Table 3.2 shows the most frequently used statistical indices for the evaluation of calibration accuracy in different published energy efficiency guidance such as that of ASHRAE, FEMP, and IPMVP. After verifying the validity of the simulation by obtaining a simple error rate, the model is considered reliable for the simulation as a base case model.

Table 3. 2 Calibration criteria of the Federal Energy Management Program (FEMP), ASHRAE Guideline 14 and International Performance Measurement and Verification Protocol (IPMVP) (Fernandez Bandera and Ramos Ruiz 2017).

Data Type	**Index**	**FEMP Criteria**	**ASHRAE Guideline 14**	**IPMVP**
Calibration criteria				
Monthly criteria %	*NMBE*	±5	±5	±20
	CV(RMSE)	15	15	_
Hourly criteria %	*NMBE*	±10	±10	±5
	CV(RMSE)	30	30	20

d) Optimisation Method

The term "optimisation" refers to the process of finding the optimal solution to a problem within a set of constraints (Huws and Jankovic 2014). In building performance optimisation, a group of parameters (x) is set according to a group of criteria, referred to as an objective function (Y), to determine the optimum solution to a problem. Single and multi-objective optimisation are two different optimisation approaches to identifying the optimal design solution (Sadeghi et al. 2021). A single-objective optimisation problem is a problem that has only one objective: one single objective function of one independent parameter Y = f(x). Single objective optimisation can effectively give the "optimal" solutions for a particular objective. However, the designers are not given any information on the effects of the variables to be optimised on the different design objectives. On the other hand, multi-objective optimisation gives designers detailed information for improved decisions (Zakaria et al. 2012).

3.3.3 Results

3.3.3.1 Descriptive analysis

A preliminary search in Scopus revealed 176 studies. Following screening of the abstracts, 93 irrelevant articles were discarded. The full texts of the remaining records were reviewed to exclude articles that did not meet the eligibility criteria. A total of 33 articles were then excluded, and 50 studies were assessed for eligibility. Thus, a total of 50 published works, including 36 articles in 23 journals, 8 conference papers published in conference proceedings, five PhD theses, and one master’s thesis were identified and included in the systematic review. These studies were carefully reviewed, and important data was extracted and analysed. Figure 3.9 shows the literature selection criteria adopted in this study. Figure 3.10 reports the number of included publications by reference type, which shows that these papers have a good quality literature basis on which to conduct the review. The final screening process, as shown in Figure 3.11 included 50 relevant studies. There are 6 studies conducted in Egypt, 5 studies in Jordan, 4 studies in Spain, 4 studies in Algeria, 4 studies in Greece, 3 studies in Morocco, 3 studies in Palestine, 3 studies in Italy, 2 studies in Turkey, 2 studies in France, 2 studies in Lebanon, 2 studies in Cyprus and 2 multi-country studies, one study in Tunisia, and one study in Libya. This illustrated that there is a scarcity of journal articles on residential building retrofit in the Libyan context. Accordingly, 6 theses from the Libyan context are added to the review.

An analysis of publication year shows that 62% of the studies were published during the last five years, while the remaining studies were published up to seven years earlier than this (Figure 3.12). This pattern suggests that energy retrofitting is currently an interesting and widely pursued research area in the region. This is due to the growing significance of energy retrofitting in residential buildings. However, there are very few studies on retrofitting existing residential stock in Libya, as only one published paper was found in relation to this (Alghoul et al. 2018), while the master's and PhD theses produced in the Libyan context are dedicated to setting a framework for designing new energy efficient residential buildings for Libya.

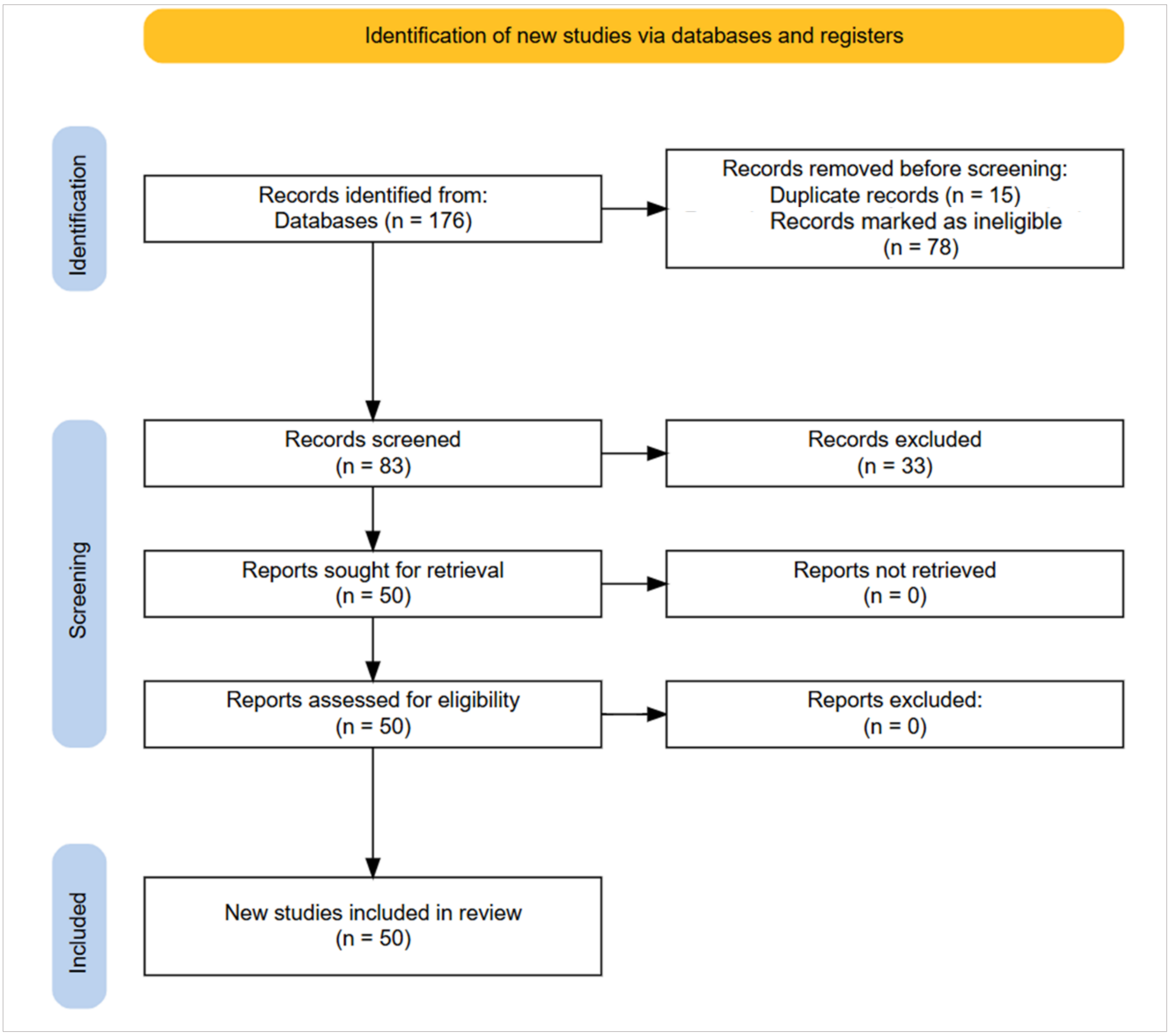


Figure 3. 9 Flow chart for the literature selection criteria

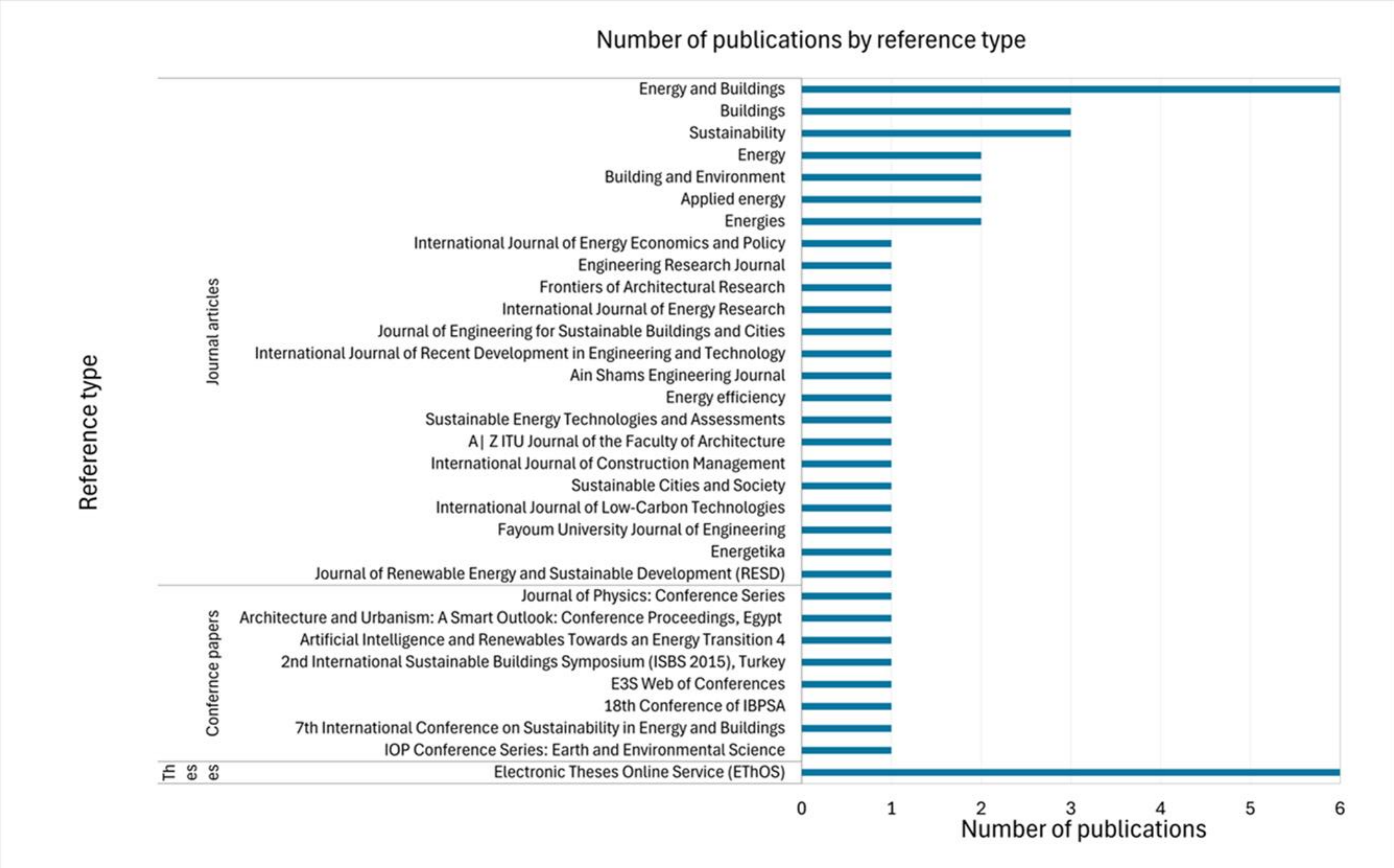

Number of publications by reference type
Reference type
Journal articles
Energy and Buildings
Buildings
Sustainability
Energy
Building and Environment
Applied energy
Energies
International Journal of Energy Economics and Policy
Engineering Research Journal
Frontiers of Architectural Research
International Journal of Energy Research
Journal of Engineering for Sustainable Buildings and Cities
International Journal of Recent Development in Engineering and Technology
Ain Shams Engineering Journal
Energy efficiency
Sustainable Energy Technologies and Assessments
A| Z ITU Journal of the Faculty of Architecture
International Journal of Construction Management
Sustainable Cities and Society
International Journal of Low-Carbon Technologies
Fayoum University Journal of Engineering
Energetika
Journal of Renewable Energy and Sustainable Development (RESD)
Conference papers
Journal of Physics: Conference Series
Architecture and Urbanism: A Smart Outlook: Conference Proceedings, Egypt
Artificial Intelligence and Renewables Towards an Energy Transition 4
2nd International Sustainable Buildings Symposium (ISBS 2015), Turkey
E3S Web of Conferences
18th Conference of IBPSA
7th International Conference on Sustainability in Energy and Buildings
IOP Conference Series: Earth and Environmental Science
Theses
Electronic Theses Online Service (EThOS)
0
1
2
3
4
5
6
Number of publications

Figure 3. 10 Number of articles per reference type

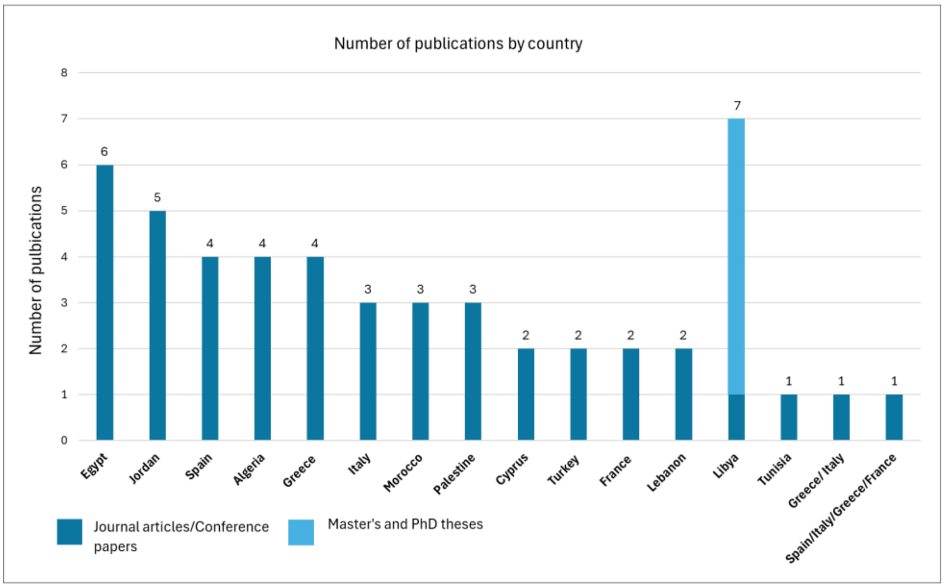


Figure 3. 11 Number of studies by country

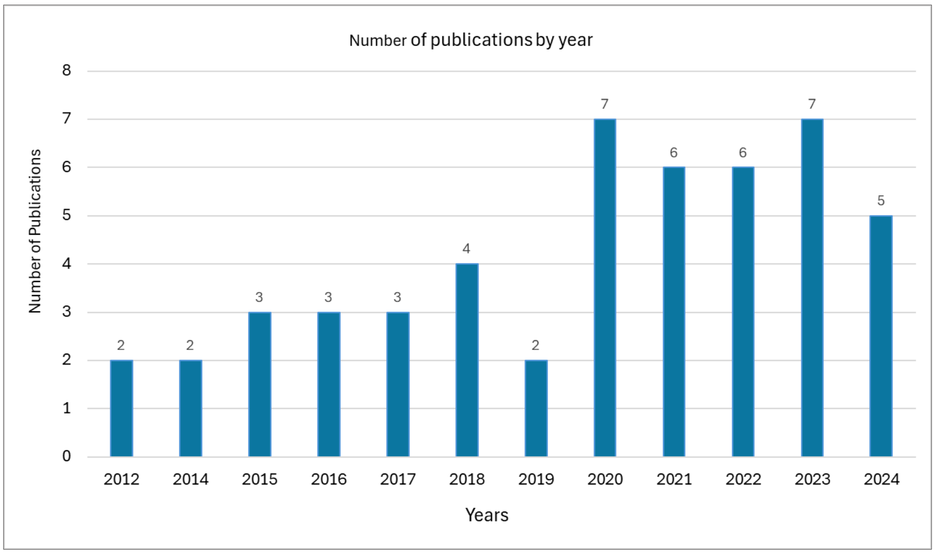


Figure 3. 12 Number of studies by year of publication.

3.3.3.2 Results of Analysis of Review Parameters

Table 3.3 shows the obtained literature for this systematic review. The review analysed each article based on four research themes identified in this review. The four themes are: a) Types of energy retrofit measures; b) building energy modelling for building retrofit; c) energy model calibration for building energy retrofits; and d) optimisation methods.

Table 3. 3 The obtained literature for this systematic review, and the themes identified to analyses the literature.

	Reference	Energy retrofit measures				BEM software		Calibration elements					Optimisation	
		Passive measures	Active measures		Embodied carbon reduction			Energy bill	Monitoring		others	Calibration indices		
			Energy efficient systems	renewable energy		3D modelling tool	Energy analysis software		Zone temperature	Energy consumption			Optimisation method	Optimisation objectives
1	(Ali et al. 2020)	x		x		DesignBuilder	EnergyPlus						SOOP	Energy saving
2	(Bataineh and Alrabee 2018)	x	x			DesignBuilder	EnergyPlus				x		SOOP	Energy saving
3	(Bataineh and Al Rabee 2022)	x	x			DesignBuilder	EnergyPlus			x		Graphical	SOOP	Energy saving Life cycle cost
4	(Attia and Zawaydeh 2014)	x	x	x		DesignBuilder	EnergyPlus						SOOP	Energy saving Cost effectiveness
5	(Albadaineh 2022)	x				DesignBuilder	EnergyPlus						SOOP	Energy saving
6	(Moraekip 2023)	x				DesignBuilder	EnergyPlus						SOOP	Energy saving
7	(Adly et al. 2020)	x	x	x		DesignBuilder	EnergyPlus						SOOP	Energy saving
8	(Darwish et al. 2024)	x			x	DesignBuilder	EnergyPlus						SOOP	Energy saving
9	(Abdelrady et al. 2021)	x				DesignBuilder	EnergyPlus	x				Correlation coefficient	SOOP	Energy saving
10	(Nafeaa et al. 2020)	x	x			Sketch-up	EnergyPlus						SOOP	Energy saving
11	(Elsheikh et al. 2023)	x				DesignBuilder	EnergyPlus						MOOP	Energy saving vs. Thermal comfort vs. Life cycle cost (LCC)
12	(Rahmani et al. 2022)	x		x		DesignBuilder	EnergyPlus						SOOP	Energy saving
13	(Hamdani et al. 2021)	x				Sketch-up	TRNSYS						SOOP	Energy saving
14	(Medjeldi et al. 2023)			x		Rhinoceros	Plugins Grasshopper and Ladybug						SOOP	Energy saving

	Reference	Energy retrofit measures				BEM software		Calibration elements					Optimisation	
		Passive measures	Active measures		Embodied carbon reduction			Energy bill	Monitoring		others	Calibration indices		
			Energy efficient systems	renewable energy		3D modelling tool	Energy analysis software		Zone temperature	Energy consumption			Optimisation method	Optimisation objectives
15	(Badeche and Bouchahm 2021)	x				Pleiade-Comfie	Comfie						SOOP	Cooling load reduction Heating load reduction
16	(Alghoul et al. 2018)	x	x	x		Sketch-up	EnergyPlus						SOOP	Energy saving
17	(Monna et al. 2021)	x	x			DesignBuilder	EnergyPlus						SOOP	Energy saving
18	(Haj Hussein et al. 2022)	x				DesignBuilder	EnergyPlus			x			SOOP	Energy saving
19	(Muhaisen 2015)	x				Visual Basic programming language	Ecotect program						SOOP	Energy saving
20	(Sobhy et al. 2021)	x				TRNSYS	TRNSYS		x			Temperature difference	SOOP	Energy saving
21	(Sghiouri et al. 2018)	x				TRNSYS	TRNSYS/jEPlus						SOOP MOOP	Energy saving/ Area weighted mean discomfort degree-hours vs. discomfort degree-hours

	Reference	Energy retrofit measures				BEM software		Calibration elements					Optimisation	
		Passive measures	Active measures		Embodied carbon reduction			Energy bill	Monitoring		others	Calibration indices		
			Energy efficient systems	renewable energy		3D modelling tool	Energy analysis software		Zone temperature	Energy consumption			Optimisation method	Optimisation objectives
22	(Abdou et al. 2021)	x		x		TRNSYS	TRNSYS			x		Mean squared error (MSE) Mean absolute percentage error (MAPE)	SOOP	Energy saving
23	(Sassine et al. 2022)	x					GenOpt and TRNSYS		x			Not mentioned	SOOP	Energy saving
24	(Nazififard and Zeynali 2024)	x		x		DesignBuilder	Energy plus/PVsyst software						SOOP	Energy saving
25	(Kutty et al. 2023)	x		x		DesignBuilder	Energy plus				x	Error rate %	SOOP	Energy saving
26	(Rosso et al. 2020)	x		x		SketchUp	EnergyPlus						MOOP	Annual energy demand vs. Annual energy costs
27	(Kitsopoulou et al. 2023)	x	x			DesignBuilder	EnergyPlus				x	Percent deviation	MOOP	Energy saving vs. Life cycle cost (LCC)
28	(Kitsopoulou et al. 2024)	x				DesignBuilder	EnergyPlus				x	Percent deviation	SOOP	Energy saving

	Reference	Energy retrofit measures				BEM software		Calibration elements					Optimisation	
		Passive measures	Active measures		Embodied carbon reduction									
			Energy efficient systems	renewable energy				Energy bill	Monitoring		others	Calibration indices		
						3D modelling tool	Energy analysis software		Zone temperature	Energy consumption			Optimisation method	Optimisation objectives
29	(Liapopoulou and Theodosiou 2020)	x		x		DesignBuilder	EnergyPlus						SOOP	Energy saving
30	(Synnefa et al. 2017)	x	x			DesignBuilder	EnergyPlus		x			CV(RSME)/MBE	SOOP	Energy saving
31	(Mangan and Oral 2014)	x				DesignBuilder	EnergyPlus Expert programme for energy generation						SOOP	Energy saving
32	(Pekdogan et al. 2024)	x				Autodesk Revit	Green Building Studio						SOOP	Energy saving
33	(Blázquez et al. 2019)	x	x	x		DesignBuilder	EnergyPlus		x			CV (RMSE), NMBE	SOOP	Energy saving Thermal comfort
34	(Caro and Sendra 2020)	x	x			DesignBuilder	EnergyPlus		x			MBE CV(RMSE)	SOOP	Energy saving Indoor CO_2 concentration
35	(Lozoya-Peral et al. 2023)	x			x	DesignBuilder	EnergyPlus						SOOP	Energy saving
36	(Garriga et al. 2020)	x	x			BEopt	EnergyPlus			x		Percentage difference	MOOP	Energy saving vs. Life cycle cost (LCC)

	Reference	Energy retrofit measures				BEM software		Calibration elements					Optimisation	
		Passive measures	Active measures		Embodied carbon reduction			Energy bill	Monitoring		others	Calibration indices		
			Energy efficient systems	renewable energy		3D modelling tool	Energy analysis software		Zone temperature	Energy consumption			Optimisation method	Optimisation objectives
37	(Ascione et al. 2019)	x	x	x		DesignBuilder	EnergyPlus	x					MOOP	Energy saving vs. cost effectiveness
38	(Ascione et al. 2016)	x				DesignBuilder	EnergyPlus						MOOP	Cooling load reduction vs. heating load reduc-tion
39	(Ali 2018)	x				DesignBuilder	EnergyPlus	x					SOOP	Energy saving Thermal comfort
40	(Eltrapolsi 2016)	x				DesignBuilder	EnergyPlus		x				SOOP	Energy saving Thermal comfort
41	(Elaiab 2014)	x				TAS 3D Modeller	TAS Simulator						SOOP	Energy saving Thermal comfort
42	(El Bakkush 2016)	x				Scratch	IES		x				SOOP	Energy saving Thermal comfort
43	(Alamri 2017)	x		x		BEopt	DOE/Homer for energy generation						SOOP	Energy saving Thermal comfort
44	(Geagea and Saleh 2023)	x		x		Revit	Revit						SOOP	Energy saving Thermal comfort
45	(Stasi et al. 2024)	x					EnergyPlus						SOOP	Energy saving Thermal comfort
46	(Serghides et al. 2015)	x				iSBEM-cy	iSBEM-cy						SOOP	Energy saving
47	(Serghides et al. 2017)	x		x		iSBEM-cy	iSBEM-cy						SOOP	Energy saving/ CO_2 reduction

	Reference	Energy retrofit measures				BEM software		Calibration elements					Optimisation	
		Passive measures	Active measures		Embodied carbon reduction			Energy bill	Monitoring		others	Calibration indices		
			Energy efficient systems	renewable energy		3D modelling tool	Energy analysis software		Zone temperature	Energy consumption			Optimisation method	Optimisation objectives
48	(Dgali 2022)	x				DesignBuilder	EnergyPlus		x	x		CV (RMSE), MBE	SOOP	Energy saving Thermal comfort
49	(Ihm and Krarti 2012)	x	x				DOE 2						MOOP	Energy Saving vs. Life cycle cost (LCC)
50	(Stazi et al. 2012)	X					EnergyPlus		x				SOOP	Energy saving Thermal comfort

a) Types of Energy Retrofit Measure

Different passive and active energy retrofit measures (ERMs) were explored in the research articles, including adding envelope insulation, replacing window glazing, adding window shading, adjusting WWR, improving airtightness, boosting night-time natural ventilation, and deploying efficient HVAC systems, lighting, and appliances, as well as integrating renewable energy sources. In the reviewed articles, passive measures showed the highest impact on reducing energy use. Moreover, adding insulation to the building envelope has the greatest impact among other passive measures. For instance, a typical two-story semi-detached house made with a reinforced concrete roof and hollow concrete block wall with no insulation located in Tripoli, Libya, was investigated using EnergyPlus simulation software with SketchUp and OpenStudio software packages (Alghoul et al. 2018). To improve the building energy efficiency of the case study building, single and combined energy efficiency measures were assessed. These include upgrading the building envelope with expanded polystyrene insulation material, upgrading the lighting system, and installation of solar water heaters and photovoltaic solar panels to cover the required energy for artificial lights. The study revealed that insulated roofs, which are responsible for the high thermal load, give the highest energy savings, followed by wall insulation. The study also found that insulating the roof is more effective in reducing the cooling load than insulating the walls, which shows a higher influence on reducing heating load than roof insulation. The study attributes this to the fact that during the summer, solar heat gain from the horizontal surface (roof) is higher than that gained by the vertical surface (walls). A similar finding is observed in the study by Stasi et al. (Stasi et al. 2024). A study was carried out to examine the application of a Phase Change Material (PCM) with a melting temperature of 25° to the external walls, and ceilings of a multi-apartment building located in Italy using an EnergyPlus tool. According to the study result, using the PCM on walls alone increases heating savings, while ceiling application maximizes cooling energy savings. Combined solutions provide the most balanced seasonal benefits, leading to the largest overall energy saving while maintaining optimal indoor comfort.

The application of insulation and dynamic thermal mass in the building envelope not only shows a significant impact on energy use reduction but also reduces indoor temperature and improves indoor thermal conditions. For instance, research was conducted on the impact of incorporating phase change material into the building envelope of a two-story house located in the Ghardaïa region, Algeria (Hamdani et al. 2021). A 3D model of the building was developed by SketchUp software, and then im-ported into TRNSYS for energy simulation. The results show that optimising the building envelope with PCM panels can contribute to annual energy reductions by up to 36.4%, and improve indoor thermal conditions, achieving indoor temperature reductions of between 2.36° C and 4° C. Elaiab (Elaiab 2014) investigated the thermal comfort and energy consumption in multi-story residential buildings in Darnah, Libya using TAS software. This study reveals that heat loss and gain through an uninsulated building envelope made of reinforced concrete roofs and cement block walls form the most influential factors in causing discomfort in both summer and winter. The study finds that a building envelope that is less responsive to the climatic conditions is responsible for almost 90% of heat gain. For the reasons stated above, this study therefore focuses on enhancing the thermal resistance of the walls, and roof. Based on the research findings, adding insulation can help to reduce heat gain by up to 63 % and lower indoor temperatures by up to 6 degrees.

Window glazing and shading showed the lowest impact on energy use reduction, and this was attributed to the low window to wall ratio (WWR) of existing buildings. Ali (Ali 2018) investigates an existing dwelling (villa) in Benghazi, Libya, using DesignBuilder software. The house is built of concrete block walls and has a reinforced concrete roof with no insulation. The monitoring and simulation study, which was carried out over a summer period, shows that the cooling load is responsible for 60% of the energy consumed. The study's results show that a prototype courtyard design inspired by vernacular architecture can contribute to substantial reductions in energy use. Insulating the building roof and walls achieved the highest energy savings, followed by improving the lighting type. However, due to the low WWR, the window & shading system showed the lowest impact compared to the other measures. Similarly, in Alghoul et al.'s study (Alghoul et al. 2018), upgrading the single-glazed windows to double-glazed windows, has the lowest impact on energy reduction.

Ground floor insulation was found to be not required for building in the Mediterranean climate. For instance, Sobhy et al. (Sobhy et al. 2021) studied a family terraced house with a reinforced concrete roof and clay brick walls, located in the climate of Morocco using TRNSYS software. The study revealed that roof insulation allows for reductions in the heating and cooling load. Adding shading devices and efficient glazing have less influence on energy reduction compared to insulating the envelope. On the other hand, slab on grade floor thermal insulation causes summer overheating, leading to an increase in demand for cooling.

Based on the reviewed articles, roof and wall insulation are found to be the most influential passive measures for improving building energy efficiency. However, 94% of the articles consider petroleum-based insulation materials such as polystyrene fiberglass and polyurethane foam, while biobased materials are only investigated in three studies. One study considers the use of hemp fibres to insulate the building envelope, finding that this material achieves the same overall annual energy requirement as when using petroleum-based insulation materials (Lozoya-Peral et al. 2023).Another study applies date palm midrib fibres for envelope insulation. The study also shows that this material improves energy efficiency effectively as an equivalent to standard insulation (Darwish et al. 2024). Dgali (Dgali

2022) investigated the impact of camel hair as insulation material on the building energy and thermal performance of Libyan houses. This study reveals that camel hair insulation has a positive impact on the hygrothermal comfort and energy performance of the Case Study Houses.

Figure 3.13 reveals the importance of passive measures in energy reduction. Upgrading the envelope with insulation materials is an approach taken by 89% of the studies, followed by replacing window glazing, adding shading, and upgrading air tightness at 54%, 38%, and 20%, of the studies, respectively. With regards to the active retrofit measures, an efficient HVAC system shows the highest impact among other active measures. Other active retrofit measures such as energy-efficient lighting and appliances show less influence on building energy efficiency and are deployed less in existing research compared to passive retrofit measures. However, the implementation of a PV system as an active renewable retrofit measure for energy generation is investigated in 44% of the research and is found to have a substantial impact on meeting a building's energy needs.

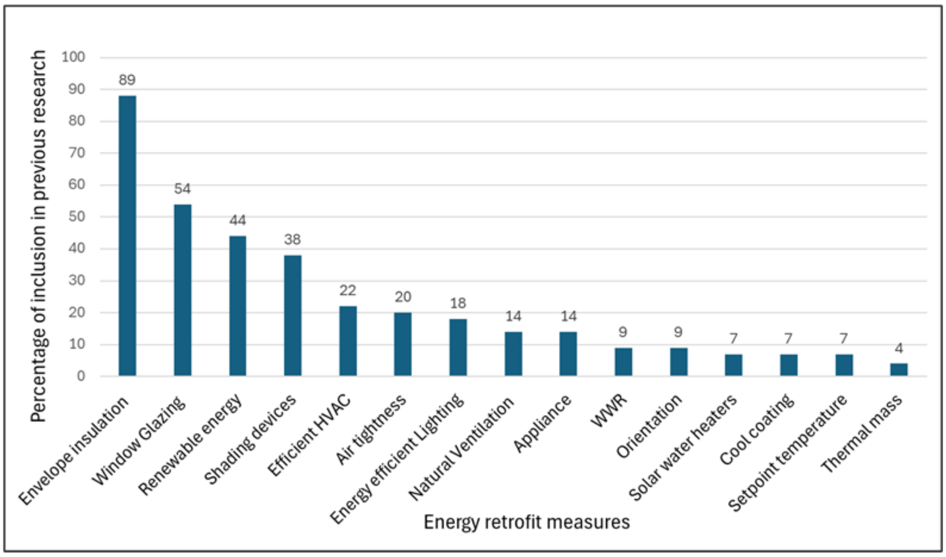


Figure 3. 13 Use of various retrofit measures in previous research

Energy Retrofit Approaches for Net Zero Energy Residential Buildings

Demand for energy worldwide is expected to increase due to population growth, the development of new cities, and the widespread use of HVAC systems (Abdou et al. 2021). As part of the global efforts towards reducing the energy use and environmental impacts of buildings and as an urgent necessity in the construction sector to achieve energy transition, the concept of net zero energy buildings (NZEBs) has emerged (Attia 2018).NZEBs are defined as "buildings that generate at least as much energy as they consume on an annual basis when tracked at the building site" (Noguchi et al. 2008). Adly et al. (Adly et al. 2020) argue that the aim of this concept is to design highly sustainable buildings that rely on two main principles: energy conservation and energy production using renewable resources. Building energy retrofitting and refurbishment through modifications has been suggested to enhance energy performance and reduce the demand for energy (Kutty et al. 2023). However, the most effective approach to achieving building energy efficiency is through incorporating renewable energy sources on-site (Ruparathna et al. 2016). Consequently, energy-efficient optimisation employing passive measures, and active measures including the integration of renewable energy sources enhance building energy performance.

Several studies have been conducted on the reduction of building energy demand to reach net zero energy buildings targets (Ascione et al. 2016; Alamri 2017; Adly et al. 2020; Ali et al. 2020; Liapopoulou and Theodosiou 2020; Rosso et al. 2020; Abdou et al. 2021; Rahmani et al. 2022; Geagea and Saleh 2023; Kutty et al. 2023; Nazififard and Zeynali 2024). For instance, Adly et al. (Adly et al. 2020) carried out a study to optimise a single-family detached house (villa) located in Cairo, Egypt, by integrating two strategies: energy efficiency retrofitting techniques to reduce energy demand, and renewable energy systems to generate sufficient energy for the building to meet net zero energy buildings targets. DesignBuilder software was used to passively optimise the building through the application of insulation materials, upgrading of window glazing and retrofitting of lighting systems. When all retrofitting types were combined, 22.6% energy reductions were achieved. The roof area allowed for installation of 44 PV panels angled at 30°, with electric power of 250 W each. The energy produced by the PV system was calculated manually. The finding revealed that 88.68% energy use reduction is achieved and NZEBs could be met by applying these two strategies. Ali et al. (Ali et al. 2020) aimed to optimise a typical house type located in Irbid-Jordan using dynamic building energy modelling (DesignBuilder) to achieve a near net zero energy building. The study utilised three optimisation stages: passive measures, active measures and integration of a photovoltaic system. The simulation results reveal that about 37.81% energy savings can be achieved by applying both passive and active measures. The study on the photovoltaic system using PVsyst software shows that integration of a PV system could reduce the energy demand further, by up to 82.41%. A study to reduce consumption and improve thermal comfort for a terraced house was conducted in Nice, France (Nazififard and Zeynali 2024). The study involved the implementation of passive measures, including the addition of insulation to the walls, roofs, and floors, upgrading windows, and minimising infiltration rate. Accordingly, the building energy demand was reduced by about 50%. To meet remaining energy needs, integrating photovoltaic panels into the building's structure as an active renewable system was studied using PVsyst software. The results reveal that the PV system covers a substantial portion of electrical energy demand. Alamri (Alamri 2017) aims to establish an optimal design for a Net-Zero Energy house in Tripoli, Libya. An existing detached house is selected and modelled and optimised by adding insulation using BEopt software. The optimisation simulation result show that the energy consumption is reduced from 7845 kWh/y to 3540 kWh/y. Renewable energy system that combines 16 solar PV system of 200W and wind turbine of 400W are modelled and simulated using homer software and MATLAB software. The simulation results reveal that this combined system was effective to supply the proposed power demand with high level of performance. Therefore, based on the reviewed articles, achieving targets around NZEBs is feasible for Mediterranean climates using a combination of passive and active renewable strategies.

b) Building Energy Modelling (BEM) for Building Retrofit

Most of the studies, at around 66%, employ EnergyPlus for building energy simulation, and mostly with DesignBuilder software, which is the most established and advanced user interface of EnergyPlus. 34% of the total studies used other building energy simulation tools. This result supports previous reviews that EnergyPlus is considered the most complete and reliable simulation tool (Sanhudo et al. 2018).

c) Energy Model Calibration for Building Energy Retrofits

The majority of the studies reviewed do not report calibrating the building energy models to ensure that the models closely represent the actual buildings (Ihm and Krarti 2012; Attia and Zawaydeh 2014; Serghides et al. 2015; Alamri 2017; Serghides et al. 2017; Adly et al. 2020; Ali et al. 2020; Nafeaa et al. 2020; Badeche and Bouchahm 2021; Hamdani et al. 2021; Monna et al. 2021; Albadaineh 2022; Rahmani et al. 2022; Felimban et al. 2023; Geagea and Saleh 2023; Medjeldi et al. 2023; Moraekip 2023; Darwish et al. 2024; Stasi et al. 2024). Some studies employ a virtual model for conducting the simulation without clarifying how reliable these models are (Krarti et al. 2020; Albadaineh 2022; Darwish et al. 2024). Therefore, these models are not fully validated as representatives of the actual buildings, and the optimisation results cannot be taken as a guide for improving the actual buildings' thermal performance.

Some studies employed electricity bills for model calibration. For example, Abdelrady et al. (Abdelrady et al. 2021) compared the simulation results with the actual energy consumption of an apartment building using the electricity bills of the third-floor apartment, to represent the average power consumption of all apartments within the building. The average error and the correlation coefficient were used as indices to calculate the discrepancy between the actual and simulated model, and both indices were found to be within the acceptable range (Abdelrady et al. 2021). Ali (Ali 2018) employed energy bills to estimate the annual energy consumption of the actual building and compare this to the annual energy consumption of the simulated building model.

Other studies employ data from previous studies or government reports to calibrate the case study building model. For instance, due to gaps in governmental reports on utility bills and consumer electricity bills, the space heat conditioning requirements obtained in a study was compared with data provided in previous research with a similar house (Kutty et al. 2023). Another study compared the baseline energy consumption of the building model with the total electricity consumed in the residential sector based on an annual government report (Bataineh and Alrabee 2018). Kitsopoulou et al. (Kitsopoulou et al. 2023) compared the thermal loads of the model simulation results with data calculated in another study for the same building model.

Only six articles adopted model calibration using measured data (Synnefa et al. 2017; Blázquez et al. 2019; Caro and Sendra 2020; Sobhy et al. 2021; Bataineh and Al Rabee 2022; Dgali 2022). Royapoor and Roskilly (Royapoor and Roskilly 2015) argued that the prediction accuracy of building energy models can be thoroughly assessed using measured data: especially with the availability of environmental and energy monitoring equipment. Bataineh and Al Rabee (Bataineh and Al Rabee 2022) measured the energy consumption data for a single day and graphically compare this with simulated data. In another study, the actual air temperature of two indoor spaces, measured for a month in the summer and a month in winter, were compared based on ASHRAE 14 calibration indices (Blázquez et al. 2019). Caro and Sendra (Caro and Sendra 2020) measured the air temperature for two indoor spaces for a typical week in the summer and used this for calibration based on the approach of the U.S. Department of Energy, which uses the indices of mean bias error (MBE) and the coefficient of variation of the root mean square error (CVRMSE) to ensure the accuracy of the simulated model. Short-term monitoring was also adopted in PhD theses to calibrate Case Study building models. For example, Eltrapolsi (Eltrapolsi 2016) employed two weeks of indoor temperature data. In another study, one summer day's indoor temperature data is compared graphically with the simulated data (El Bakkush 2016). However, for robust model calibration, and to ensure that the model represents the actual building performance over the year, data measured over a long time and in different seasons of the year are required to avoid discrepancies.

d) Optimisation Method

With regards to the optimisation methods used, the majority of these studies adopted a single-objective optimisation problem (SOOP), which aims to optimise one parameters at a time or multi-variants at a time against one objective function (Stazi et al. 2012; Muhaisen 2015; Synnefa et al. 2017; Bataineh and Alrabee 2018; Adly et al. 2020; Ali et al. 2020; Liapopoulou and Theodosiou 2020; Abdou et al. 2021; Albadaineh 2022; Bataineh and Al Rabee 2022; Sassine et al. 2022; Moraekip 2023; Darwish et al. 2024; Kitsopoulou et al. 2024). On the other hand, the multi-objective optimisation problem (MOOP), which helps in making decisions that consider trade-offs between two conflicting objectives, was adopted in only 7 articles. For example, three studies investigated the trade-off between energy saving and life-cycle cost (LCC) (Ihm and Krarti 2012; Garriga et al. 2020; Kitsopoulou et al. 2023). Ascione et al. (Ascione et al. 2016) investigated the optimal trade-off between summer and winter energy performance. However, despite the importance of thermal comfort investigations in building retrofits, none of the reviewed research considered the use of a simulation-based multi-objective optimisation problem to determine the trade-off between energy usage and thermal comfort, including that in the Libyan context.

3.3.3.3 Research Gap

The results of this review reveal research gaps in existing literature. Limited attention has been paid to retrofitting existing housing stock in the context of Libya. In addition, few research reviewed here aims to achieve a net zero energy level for Libyan housing stock. Therefore, further study is needed to investigate the potential for meeting net zero energy buildings targets through the integration of a PV system for Libyan housing using the building energy modelling (BEM) tool.

Although DesignBuilder enables the modelling of solar photovoltaic power systems, none of the studies that deploy DesignBuilder for model simulation have exploited this feature to investigate the potential for meeting the building energy levels needed to achieve the NZEBs target. Consequently, meeting energy building needs and achieving NZEBs targets by integrating passive retrofit measures and on-site PV energy generation system using DesignBuilder would be a novel methodological contribution to the existing literature.

A major weakness in the literature is represented by the credibility of the energy models, wherein most of the studies reviewed, including that on Libya, were carried out without ensuring the reliability of the energy model and rely on assumptions for their model setup, which would affect the accuracy of the simulation results. Measured data, which is essential for building model setup and for understanding the prediction accuracy of the building model, is adopted in several studies. However, the measurement of the environmental data and energy consumption in these articles covers only a short period, which could lead to discrepancies between the actual building's energy use and the building energy model. Consequently, for robust model calibration, and to ensure that the model represents actual building performance, building monitoring over the whole year is necessary.

Model calibration on a monthly and hourly basis is also needed to ensure that the building model closely represents the actual building (ASHRAE14 2002). In addition, measuring the total energy of the building as well as the energy used by each category across the whole year would provide important information through which the categories responsible for the greatest energy consumption could be identified and thus the appropriate energy retrofit measures determined. Further important data that, if not specified accurately, could have an impact on the accuracy of the energy model of an existing building is the thermal transmittance of the building envelope (U-value). Information about the structure and materials of the existing building envelope may not be accurate or may be unavailable. As a result, it would be beneficial to employ on-site measurement as a current approach for evaluating the thermal properties of the existing building envelopes of different residential building types in Libya using a heat flux sensor, which would form an addition to existing literature on building energy retrofits in Libya.

Reducing energy consumption could have an impact on indoor thermal comfort. However, the trade-off between energy consumption and thermal comfort has not been comprehensively investigated in previous research, including that in the Libyan context. Therefore, the balance between energy consumption and thermal comfort needs to be explored using a multi-objective optimisation problem. While this approach is an existing feature in DesignBuilder, none of the studies reviewed that used DesignBuilder for energy simulation employed this feature. Consequently, use of this tool would form a methodological addition to the existing knowledge of residential building retrofits in Mediterranean countries, including Libya, to find an optimal solution that achieves a trade-off between energy saving and thermal comfort. Embodied carbon reduction in building retrofits needs to be considered. Biobased insulation materials for example are renewable and contribute to reducing the embodied carbon of the building. However, most of the previous research, including that in the Libyan context, has deployed petroleum-based insulation materials, and only three research investigated biobased insulation materials. Accordingly, further studies to investigate the effectiveness of different biobased insulation materials on energy reduction in Libyan housing stock would be an additional contribution to existing knowledge.

3. 4 Chapter Summary

This chapter provides a general review of relevant knowledge in the research field of building energy retrofits, and highlighting different energy retrofit measures for residential buildings in hot climates. A systematic review was carried out to explore the existing research and knowledge gaps in published research focusing on energy retrofits in existing residential buildings located in Libya and neighbouring Mediterranean countries. Using search terms and keywords which were carefully selected to focus on the purpose of this systematic review, 50 relevant studies were found. Most of these were published in the last five years, but due to the limited number of publications within the research context, published literature dating back to 2012 and some PhD theses were also included in the systematic review. Following the initial review, the articles were reviewed and analyzed based on four themes identified in this review. Finally, the systematic review concluded with a discussion on content analysis and identifying knowledge gaps and future research directions.

Chapter 4: Research Methodology

4.1 Introduction

This chapter comprises an outline of the methods selected to achieve the research aim. This aim is centred on identify the optimal solutions for retrofitting existing residential building stock in Libya to meet net zero energy buildings (NZEBs) targets by proposing a hybrid retrofit approach. To achieve the research aim, empirical and numerical simulation approaches were adopted. Three different case studies representing residential building typologies in Benghazi were monitored to assess their thermal and energy performance and to collect the data required to generate and calibrate the case study building models. This chapter illustrates the criteria for selecting and monitoring the case study buildings and defines the monitoring equipment and methods used for data collection. A description of the methodology for calibrating and simulating the case study models is also explained. Finally, a description of the optimisation approach is given.

4.2 Research Methodology

The research approach combines case study monitoring (empirical study), and numerical simulation study (Figure 4.1).

a) Thermal Performance and Energy Consumption Monitoring of Case Study Buildings (Empirical Study)

Three different case study buildings: a terraced house, detached house (villa), and apartment building were selected and monitored for their energy consumption, and outdoor and indoor thermal conditions. The data collected through monitoring the buildings were firstly used to obtain an overall view of each building's thermal and energy performance. Secondly, the collected data was used to create computer models in a simulation tool to investigate the influence of implementing different energy retrofit measures on energy and thermal performance for the selected buildings, and to investigate the potential for meeting the requirements of net zero energy buildings (NZEBs).

b) Building Modelling and Simulation in DesignBuilder (Numerical Study)

The building modelling and simulation phase for the current study necessitates selection of simulation approach and software in order to construct a realistic model that imitates the actual cases. This phase utilised DesignBuilder software and modelling based on the collected data from monitoring the case study buildings, as well as occupant feedback during the building's survey. The case study buildings models were calibrated based on ASHRAE Guideline 14-2002 calibration criteria, using both actual energy consumption and indoor zone temperatures to enhance the accuracy of the simulation outputs(ASHRAE14 2002). The models were then optimised by applying single and combined retrofit measures. The optimised case simulation results were compared with base case simulation results to determine the optimal design solution for reducing energy consumption without compromising thermal comfort. Further optimisation was carried out to meet remaining energy needs by integrating a PV system to achieve the requirements of the NZEBs. The following sub-sections provide further details on the selected methods.

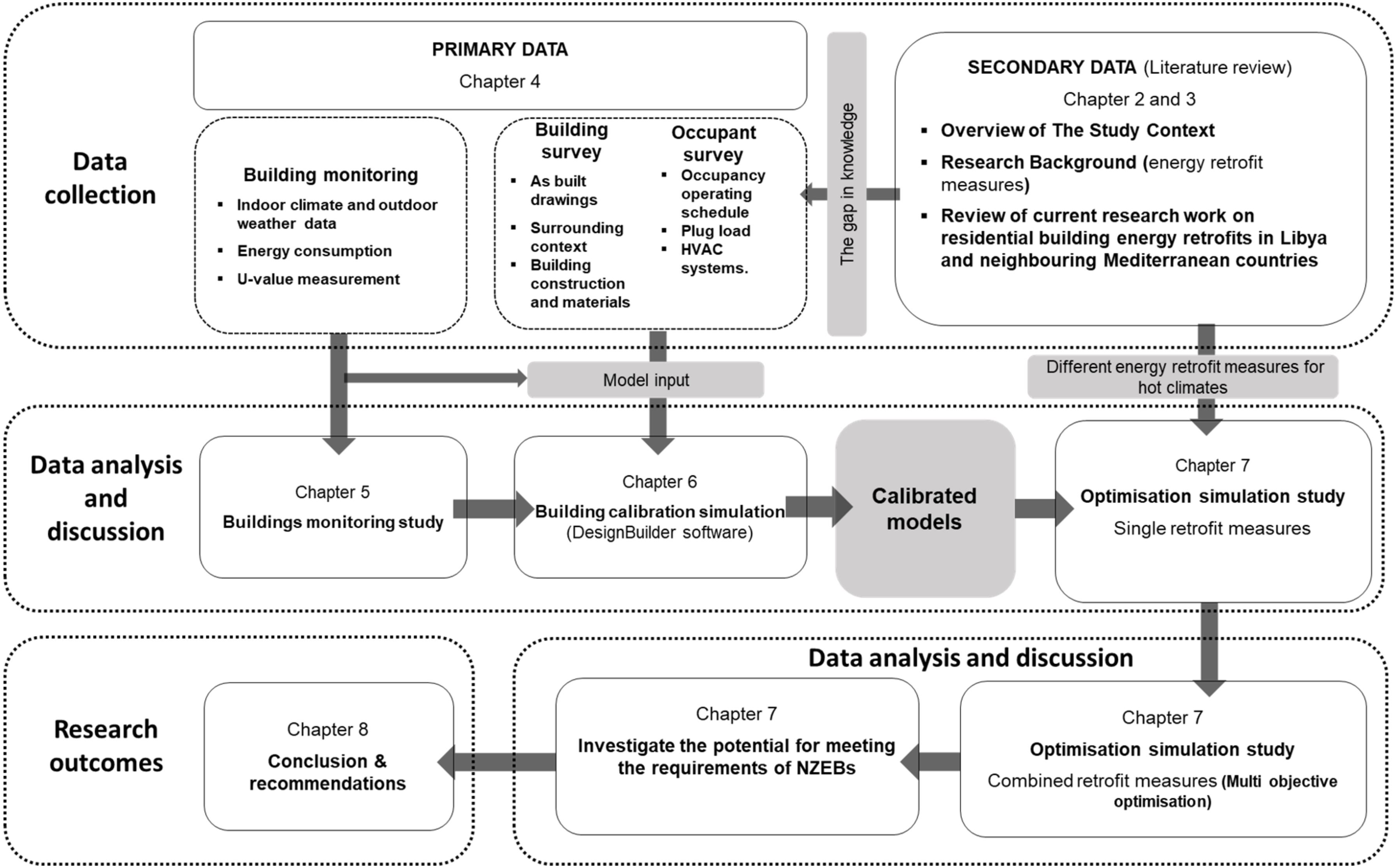


Figure 4. 1 Outline of the research approach

4.2.1 Case Study Selection

This section clarifies the reasons for choosing the case study buildings for investigation and describing their main features. Chapter 2 introduced an overview of the national housing typologies in Benghazi (UPA 2009). Recalling the findings, terraced houses are the dominant type of dwelling, which account for about 70% of the national stock. This terraced house type, as mentioned in Chapter 2, was built in the 1970s of the last century. However, due to changes in Libyan government policies, this style of house is no longer constructed, although vertical extension of these buildings has taken place in later years (Almansuri 2010). Detached houses (villas) constitute approximately 20% of the housing stock, while apartment buildings constitute the lowest percentage at about 10%. The villa model and apartment buildings emerged as significant construction trends in the 1980s and are still built today (UPA 2009).

Selecting terraced houses for investigation is reasonable as this housing type represents the dominant style of dwelling in Benghazi and has significant potential for energy saving. However, because the most recent housing statistics for the city date back almost two decades (UPA 2009), it is realistic to assume that there has been some percentage change from this picture. While there has been an increase in the construction of detached houses (villa model) and apartment buildings over the past several decades, the terraced house model has not been constructed since the 1980s. Hence, in terms of energy conservation potential, other housing types (detached house and apartment building) are as important to consider as the terraced house. Therefore, it is vital to include all types of existing housing types in the current study. After speaking to a number of Benghazi residents to explain the purpose of the study and how the research findings would bring numerous benefits in the future, such as improving thermal comfort inside buildings and reducing electricity bills, the researcher was welcomed by several residents to enter their homes, install the monitoring devices, and arrange convenient times to visit their buildings to collect data from the devices. Three case study buildings (a terraced house, detached house, and apartment building) were selected to serve as representative of residential buildings in Benghazi, for the following reasons:

1. They were built with construction materials common to Benghazi

2. They have a design, layout, and floor area typical to most dwellings in Benghazi.

3. The number of occupants in these buildings represents the average Libyan household (5 people).

4. Each of the case study buildings are occupied by Libyan families who have a comparable lifestyle, cultural background, and occupancy pattern.

5. Accessibility of the case study buildings.

Figure 4.2 shows the locations of the case study buildings in the city of Benghazi.

Figure 4. 2 Case study building locations

4.2.1.1 Case Study 1 (Terraced House)

The house is a two-storey building and covers an area of about 300m^2. The exterior walls of the terrace house are adjacent and shared by the attached houses from the back and sides which may provide them with some protection from the external conditions, while the front facade faces the open front yard (Figures 4.3 - 4.4). The house also consists of two small courtyards between rooms to facilitate natural ventilation and daylight. The larger courtyard is exposed to more solar radiation than the smaller one, which is partially shaded by the surrounding walls.

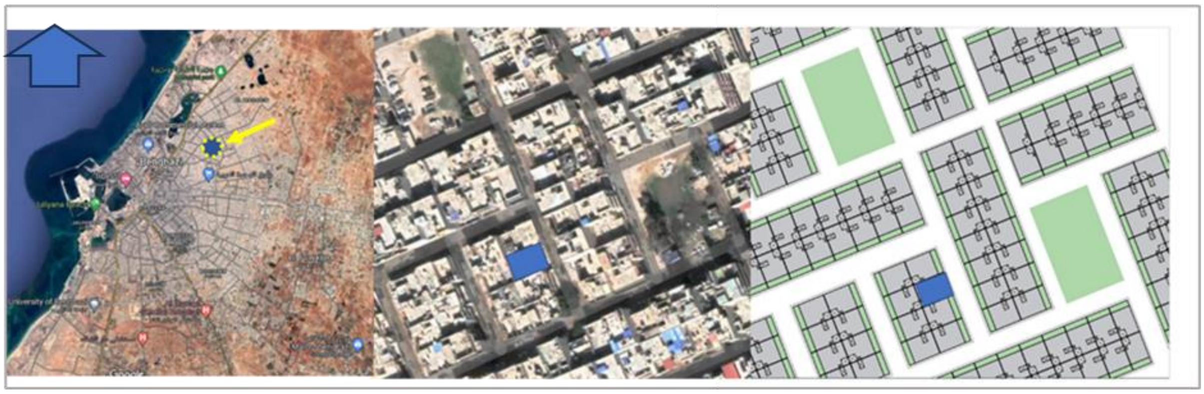


Figure 4. 3 Terraced house location

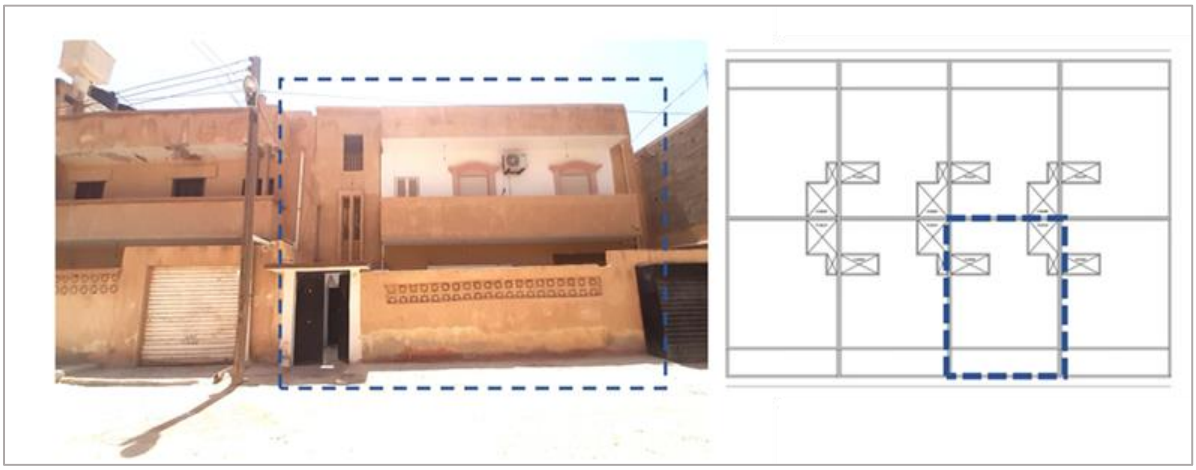


Figure 4. 4 Terraced house form and site layout

Each floor consists of two bedrooms, a living area, a reception area, a kitchen, and a bathroom (Figure 4.5). The building adopts mixed ventilation strategies (natural and mechanical) for cooling the indoor spaces. Natural cooling in summer is aided by the small courtyards. The floors also benefit from mechanical cooling via one split air conditioner on each floor. For heating in the winter, electric heaters are used. The ground floor (GF) of the house is 147 m² and is constructed in 1976, with a reinforced concrete ceiling and limestone brick walls covered by cement plaster on both sides. The first floor (FF) is 152 m² and is built in 2013, with a reinforced concrete roof and hollow concrete block walls covered by cement plaster on both sides. The house is constructed without any insulation in the envelopes: this practice is common in Benghazi's residential buildings (Ali 2018).

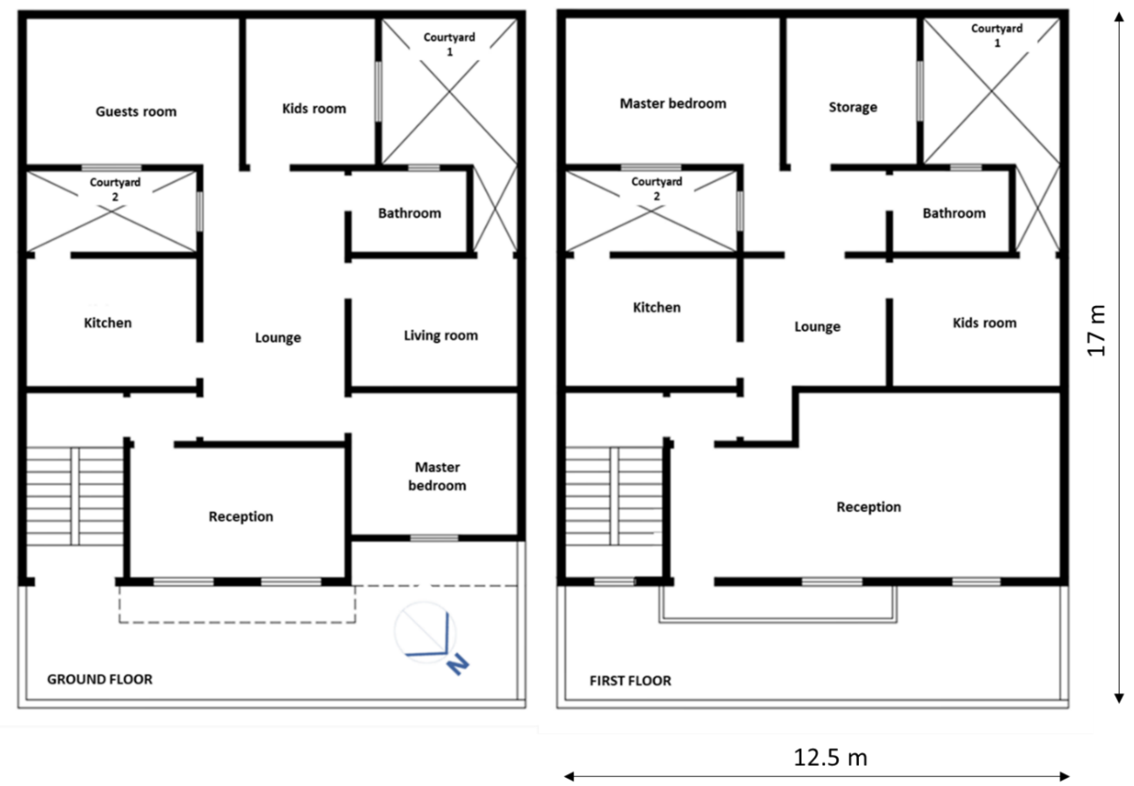


Figure 4. 5 Terraced house design layout

4.2.1.2 Case Study 2 (Detached House)

The detached house is a one-storey building located in the southeast of Benghazi (Figures 4.6 - 4.7). Its floor area is 230 m², whereas the site area is approximately 400 m². The building is surrounded by an open space which separates it from neighbouring dwellings and plays a role in providing the inside with privacy, lighting and ventilation. The building consists of three bedrooms with a bathroom, a living area attached to an open kitchen, a Lounge, guest room and a reception with a toilet (Figure 4.8).

Figure 4. 6 Detached house location

Figure 4. 7 Detached house form and site layout

Figure 4. 8 Detached house design layout

4.2.1.3 Case Study 3 (Apartment Building)

The building for case study 3 is a four-storey apartment building located in the north of Benghazi (Figures 4.9- 4.10). Each floor consists of two flats, and the building reflects the typical design of apartment buildings in the city. The flat monitored for the study is situated on the top floor and is selected particularly as it represents the worst-case scenario in terms of heat gain and loss. Each flat consists of two bedrooms with bathroom, living area, kitchen, and reception with toilet (Figure 4.11).

The building covers a ground area of about 300 m², with a total floor area of approximately 1200 m². Each flat is approximately 150 m² in area and is attached to the neighbouring flat from one side, while the other three sides are exposed to the outside. The building was built in 2015, with a reinforced concrete roof and hollow concrete block walls covered by cement plaster on both sides, and without any insulation on the envelope. All indoor spaces receive natural ventilation and daylight from the outside, except for the kitchen, which obtains daylight and ventilation from the inner courtyard.

More information on the case study buildings can be found in Tables 4.1- 4.2.

Figure 4. 9 Apartment building location

Figure 4. 10 Apartment building form and site layout

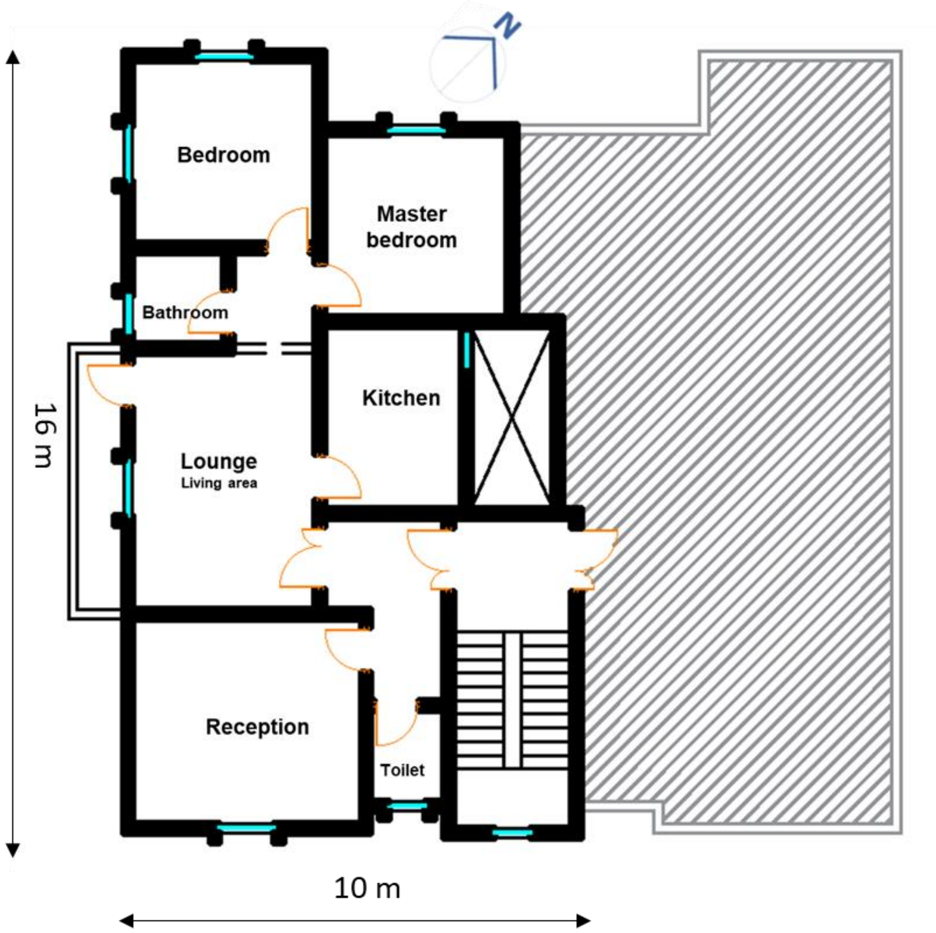


Figure 4. 11 Flat design plan

Table 4. 1 Case Study buildings information

Criteria	**Case Study 1**	**Case Study 2**	**Case Study 3**
Type, Design, and Layout	Terraced house, consisting of living room, three bedrooms, guest room and reception.	Detached house, consisting of living room, three bedrooms, guest room and reception.	Apartment building of 8 flats. Each flat consists of living room, two bedrooms, and reception.
Floor area	GF 147 m^2	230 m^2	

	FF 152 m^2		1200m^2 , 150 m^2 for each flat
Orientation	NE	NW	SE
Envelope	GF Wall: Limestone block, FF Wall: hollow concrete block Roof: reinforced concrete slab Windows: single-glazed windows	Wall: Hollow concrete block Roof: reinforced concrete slab+ hollow blocks Windows: single-glazed windows	Wall: Hollow concrete block Roof: reinforced concrete slab+ hollow blocks Windows: single-glazed windows
Occupancy	Five people in each floor	Five people	Five people in the monitored flat
Equipment	Mechanical cooling for summer and electrical heating in winter	Mechanical cooling for summer and electrical heating in winter	Mechanical cooling for summer and electrical heating in winter

Table 4. 2 Construction materials of the case study buildings

	Material description	Layer order
	Case Study 1	
GF Wall	10mm cement mortar + 180mm limestone block+10mm cement mortar + 5mm gypsum plaster	External to internal
GF Celling	10mm ceramic tiles + 10mm cement mortar + 200mm reinforced concrete slab + 10mm cement mortar + 5mm gypsum plaster	Top to bottom
GF Floor	10mm ceramic tiles + 10mm cement mortar + 200mm concrete slab + 500mm sand and gravel	Top to bottom
FF Wall	20mm cement mortar + 200mm hollow concrete block+	External to internal

	20mm cement mortar + 5mm gypsum plaster	
FF Roof	50mm cement mortar + 200mm reinforced concrete slab + 10mm cement mortar+5mm gypsum plaster	Top to bottom
	Case Study 2	
wall	20mm cement mortar + 200mm hollow concrete block+20mm cement mortar + 10mm gypsum plaster	External to Internal
Floor	Floor 10mm ceramic tiles +10mm cement mortar + 150mm concrete slab	Top to bottom
Roof	20mm cement mortar + 100mm reinforced concrete slab + 100mm hollow concrete block + 20mm cement mortar +5mm gypsum plaster	Top to bottom
	Case Study 3	
Wall	20mm cement mortar +200mm hollow concrete block+20mm cement mortar+ 10mm gypsum plaster	External to Internal
Floor	10mm ceramic tiles+10mm cement mortar + 150mm concrete slab	Top to bottom
Roof	20mm cement mortar + 100mm reinforced concrete slab + 100mm hollow concrete block + 20mm cement mortar + 5mm gypsum plaster	Top to bottom

4.2.2 Building Survey and Monitoring

A building survey and monitoring were carried out for the three case study buildings to assess and understand their energy and thermal performance, which as a result helped in selecting the most appropriate solution for retrofitting. The data collected from monitoring and surveying the buildings was also used as input data to develop and calibrate the buildings models.

4.2.2.1 Building Survey

The researcher conducted a survey to collect information about the building materials, geometrical parameters, site and occupants to identify the relevant spaces for monitoring, including function and occupancy patterns. The data collected was used to set up a numerical model for each building.

Site information: Information was collected on the natural and artificial context, such as surrounding buildings and vegetation.

Building information: Information collected included geometrical data, age, orientation, access, views, number of storeys, structure, fabric details (materials and layering), openings and glazing ratio, type, frames, identification of relevant spaces for monitoring, and data about function.

Service systems information: Information was collected on all the systems present, both electrical and mechanical, such as HVAC types and number, cooling setpoint, and the number and capacity of appliances and lighting.

Occupancy pattern: during the building observations, the researcher collected information on weekday and weekend occupancy and operation schedules.

4.2.2.2 Monitoring Period

Energy consumption and outdoor weather conditions were monitored over a one-year period, from June 2022 to July 2023. Indoor climate conditions for each building were monitored for three months: one month in the summer one month in the winter, and one month in the transition season. Indoor climate conditions were monitored for the three different case study buildings during different periods, as shown in Table 4.3.

Table 4. 3 Indoor thermal condition monitoring plan

	Case study 1	**Case study 2**	**Case study 3**
Summer	8th JUN 2022- 7th JUL 2022	7th JUL 2022- 5th AUG 2022	7th AUG 2022- 6th SEP 2022
Winter	12th DEC 2022- 10th JAN 2023	15th JAN 2023-13th FEB 2023	15th JAN 2023-13th FEB 2023
Transition season	20th OCT 2022-20th NOV 2022	1ST APR 2023-30th APR 2023	1ST APR 2023-30th APR 2023

4.2.2.3 Building Monitoring

More information on the case study buildings' performance in response to weather fluctuations over a long period is needed to facilitate the retrofit decision-making process. The researcher set up a weather station to obtain real outdoor weather data along with a manual solar radiation detector to measure solar radiation over a one-year period. A Bluetooth sensor logger was used to monitor indoor temperatures for only one month each season, including a transition season, for each case study building. The annual energy consumption of the case study buildings was recorded over a year period using current clamps and a data logger, along with a socket energy meter. A heat flux sensor was used to measure the U- value of the existing wall constructions. All monitoring devices were set to take data every 30 minutes. These devices were selected for building monitoring because of their high-accuracy measurements, and ease of setup and usage. Information on the setting and installation of the monitoring devices can be found in Appendix A1.

4.2.2.3.1 Description of the Monitoring Equipment.

- **Outdoor Weather Data**

Outdoor weather data were collected using the EnviroTrack Weather Station & Data Logger. However, since this device does not contain a solar radiation sensor, a manual solar radiation detector was used, and the collected data were compared with the relevant TMY weather file date to ensure solar radiation data was close to actual data. The solar radiation data in the EPW file was in good agreement with the data measured by the manual sensor. Therefore, solar radiation data for the EnergyPlus weather file were left unchanged. Table 4.4 shows the variables measured by the weather station and details regarding accuracy. Table 4.5 describes the specifications for the solar radiation detector. The data collected were used to create an EPW file for model setting, calibration, and simulation.

Table 4. 4 EnviroTrack Weather Station & Data Logger - USB Data Communication (Tempcon Instrumentation, West Sussex, UK)

		Specifications			
	Temperature	Relative humidity	Wind speed	Wind direction	Rain
Measurement range 	-40°C to 75°C (-40°F to 167°F)	0-100% RH at -40° to 75°C (-40° to 167°F); exposure to conditions below -20°C (-4°F) or above 95% RH may temporarily increase the maximum RH sensor error by an additional 1%	0 to 76 m/sec (0 to 170 mph)	0 to 355 degrees	0 to 10.2 cm (0 to 4 in.) per hour, maximum 4,000 tips per logging interval

Accuracy	±0.21°C from 0° to 50°C (±0.38°F from 32° to 122°F); see Plot A	±2.5% from 10% to 90% RH typical to a maximum of ±3.5% including hysteresis at 25°C (77°F); below 10% and above 90% ±5% typical	±1.1 m/sec (±2 mph) or ±5% of reading, whichever is greater	±7 degrees	±4.0%, ±1 rainfall count between 0.2 and 50.0 mm (0.01 and 2.0 in.) per hour; ±5.0%, ±1 rainfall count between 50.0 and 100.0 mm (2.0 and 4.0 in.) per hour
Resolution	0.02°C at 25°C (0.04°F at 77°F); see Chart A	0.1% RH	0.5 m/sec (1.1 mph)	1 degree (0 to 355 degrees)	0.2 mm
Operating Temperature Range	-40°C to 75°C (-40°F to 167°F)		-40°C to 65°C (-40°F to 149°F)		0° to 50°C (32° to 122°F), survival -40° to 75°C (-40° to 167°F)

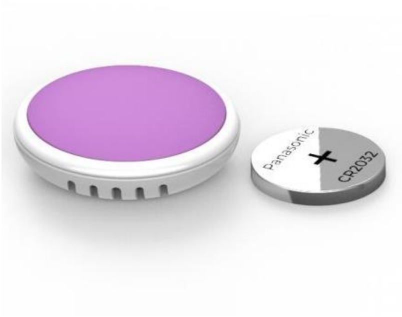
Table 4. 5 Solar radiation detector PCE-SPM 1 (PCE Instruments UK Ltd., Manchester, UK)

Specifications	
Measuring range	0 ... 2000 W/m²
Resolution	1 W/m²
Accuracy	±10 W/m² or ±5 %
(the higher value applies)	
Spectral range	400 ... 1100 nm
Data memory	32,000 readings
Measuring rate	Adjustable
Data transmission	serial RS-232 interface
Display	LCD
Ambient temperature range	0 ... +50 °C / 32 ... 122 °F
Max. humidity	<80 % RH
Operating supply	4 x 1.5 V AAA Li-ion batteries
(for approx. 16 days of continuous use)	
Dimensions	111 x 64 x 34 mm / 4.3 x 2.5 x 1.3"

- **Indoor Climate Monitoring**

Tempo Disc Bluetooth sensors were used to measure indoor climate conditions. The data was collected from sensors wirelessly using the Tempo plus application, then transferred to the computer as a CSV file for initial data analysis, and for model calibration. Table 4.6 shows the specifications of the Tempo Disc Bluetooth sensors.

Table 4. 6 Tempo Disc™ 4 in 1 Bluetooth Sensor Logger (Blue Maestro, USA)



Specifications	
Readings	18000 (approx.)
Logging interval	1 second to 18 hours
Battery life	Up to 12 months
Temperature and dewpoint accuracy	Typical 0.3ºC with maximum 0.4ºC at -10ºC to +75ºC
Temperature reading range	-30ºC to +75ºC
Temperature response time	3.8 minutes
Humidity reading resolution Accuracy	Typical 3% RH with maximum 4% RH 0-80% RH
Humidity reading range	0% to 100%

- **Thermal transmittance (U-value) measurement**

Thermal transmittance is important in understanding how quickly heat moves through a material or structure. Because of this, it is vital to properly define thermal transmittance in order to establish effective means of saving energy (Bienvenido-Huertas et al. 2019). However, calculating the thermal transmittance (U-value) of existing dwellings can be uncertain or difficult because information about the structure and materials of the building envelope may not be available (Chen 2018). For this reason, on-site measurement helps gain a more accurate estimation (Ficco et al. 2015; Teni et al. 2019). The measurement of two different wall constructions was carried out, following ISO 9869-1:2014 (ISO 2014). The U-values of the buildings' walls were obtained by measuring the heat flow rate and temperatures on both sides of the selected walls with a heat flux meter (HFM). The measured values were used to assess the thermal performance of the building envelope and as input data for model setup. Table 4.7 shows the specifications of the heat flux sensor.

Table 4. 7 U-value and heat flux sensor specifications (GreenTEG, Switzerland)

	Specification

Product	gSKIN® KIT-2615C (calibrated) Measurement of U-value (W/(m²K)), heat flux (W/m²), and 2 temperatures (°C). Compatible with standards ISO 9869 and ASTM C1046 /ASTM C1155.
Heat Flux Range Min / Max	±300
Heat Flux Resolution [W/M²]	<0.22
Temperature Accuracy [°C]	±0.5 (-10...+46 °C) ±2.0 (-55...+125 °C)
Min. Sensor Sensitivity (S) [MV/(W/M²)]:	7.0 (sensor calibration data already loaded onto logger for simple and fast plug-and-play measurements).
Minimum temperature difference between inside and outside	5°C
Data Storage Capacity [# Measurements]	>2'000'000
Battery Lifetime [Days]	>30 at lowest measurement frequency (2/d). Rechargeable.
Calibration Accuracy [±%]:	3 (Sensor calibration data already loaded onto logger for simple and fast plug-and-play measurements).
Measurement Frequency:	1/s to 1/h

- **Energy Consumption**

The case study buildings are supplied by grid electricity. Energy consumption was measured using two different energy meters: Tiny-Tag current clamp meters with data loggers; and socket energy meters. The measured data was used to assess building energy performance and to calibrate building models. Tables 4.8 - 4.9 provide a description of equipment specifications and level of accuracy. The current was measured at sub- hourly time intervals. At the period of the current measurement, the recorded voltage was varying between 191V, 200V, 210V, and 215V. The measured voltage was within the range of the plug-in meters. The average of these observed values was employed for the calculation. The energy consumption of the case study buildings was calculated by the following equation:

Energy consumption= ((Current ×Voltage)/1000) × 0.5 (4.1)

Step 1: To calculate the watts, the current values in amps (A) were multiplied by the voltage (V).

Step 2: To convert the W to kW, the values obtained from step (1) were divided by 1000.

Step 3: Because the measured data was in sub-hourly time intervals, the values obtained from step (2) in kW were multiplied by 0.5 to convert the kW to kWh.

Table 4. 8 Tiny-Tag View 2 Current Logger (Gemini Data Loggers, UK)

Specifications	
Total reading capacity	30,000 readings
Reading types	Actual, Minimum, Maximum
Logging interval	1 second to 10 days
Battery life	Up to 12 months
Reading range	0.15 to 200A AC
Frequency range	40Hz to 10kHz
Maximum current	240A AC*
Reading resolution	10 mA
Display resolution	0.1A
Accuracy	0.5A to 10A (5% of reading +/-0.5A) 10A to 40A (3% of reading +/-0.5A) 40A to 200A (2% of reading +/-0.5A

Table 4. 9 Socket energy meter (RS, UK)

Specification	
Operating voltage	230V, 50HZ
Operating current	max 16A
Wide voltage range	230V---250V
Timing display range:	0 second---9999 days
Wattage display (watts)	0W---9999W
Voltage display range	0V---9999V
Current display (amps)	0.000A—16.000A
Frequency display	0Hz---9999Hz
Minimum Wattage display range	0.0W---9999W
Maximum Wattage display range	0.0W---9999W
Total KWh and cost display	0.000KWH---9999KWH, 0.00COST ---9999COST

Measurement errors

The monitoring devices were carefully selected in terms of accuracy to reduce the degree of measurement error. The weather station, for example, has an error rate of only ±0.21°C in temperature measurement, ±2.5% in measuring relative humidity, and ±1.1 m/sec in measuring wind speed. Indoor sensors have an error rate of ±0.4°C in measuring the temperature, and 4% in measuring the relative humidity. No errors occurred in the monitoring data. However, because the batteries for indoor sensors have short lifespans, some of the sensors stopped recording for a short time during the monitoring period. Data from these sensors have been excluded in the data analysis and this had no impact on building assessment or model calibration.

4.2.2.3.2 Sensor Location and Placement

- **Outdoor weather sensors**

The weather station was set up on the roof of the terraced house building (Case Study 1), which is located at roughly mid-distance between the other case studies. It was set up at about 10 m above street level, and there were no nearby obstructions that might affect the direction or speed of the wind (Figure 4.12). It was left on the terraced house roof to record outdoor weather over the whole monitoring period (one year) from June 2022 to July 2023.

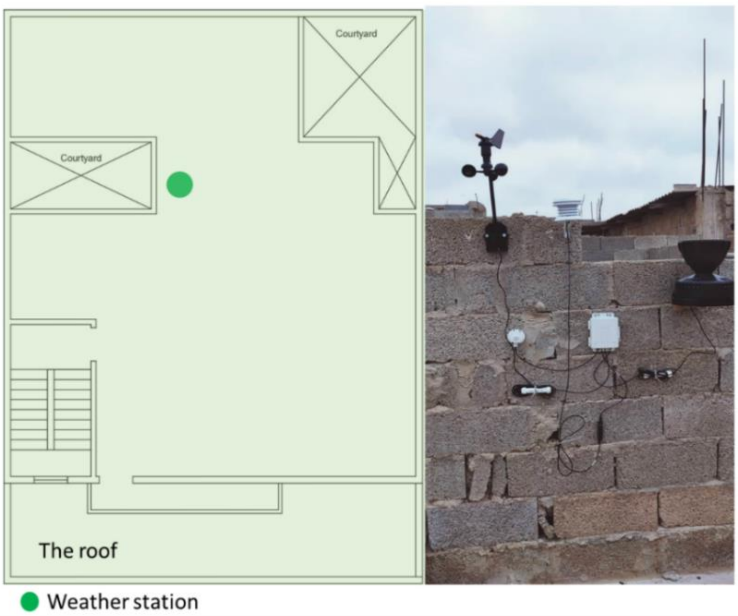


Figure 4. 12 Weather station location and installation on the building roof

- **Indoor climate sensors**

Case study 1

Bluetooth sensors were installed in all indoor spaces of Case Study 1, including the bedrooms, living rooms, kitchens, bathrooms, receptions, guest rooms and the courtyards (Figure 4.13). To reduce errors in measuring indoor thermal conditions, the sensors were placed away from the impact of any external variables that might affect reading accuracy, such as solar radiation, wind, or any other sources of heat or moisture. The indoor spaces are 3.50 m high on both ground and first floors. Hence, the sensors were mostly placed at about 1.5 m high. However, in some spaces, the sensors were placed at around 2 m high to keep them away from the reach of children. Using Tempo Plus 2 software, each sensor is named according to where it is located to facilitate and avoid mistakes while collecting the data.

Figure 4. 13 Plan shows the indoor sensor locations on both the ground and first floor of Case Study 1

Case study 2

As shown in Figure 4.14, Bluetooth indoor sensors were installed in all indoor spaces of Case Study 2. Most of the sensors are situated at around 1.5m high, except for the kitchen and the bedrooms, where the sensors were situated at 2m high.

Figure 4. 14 Plan shows indoor sensor locations in Case Study 2

Case study 3

Bluetooth sensors were placed in all indoor spaces of the monitored flat (Figure 4.15). Two further sensors were placed in the bedroom and lounge of the lower flat (3rd floor flat) in the summer only. Since the other flats were inaccessible, no sensors were installed in them. The sensors were placed at 1.5 m and in some spaces at 2m high to keep them away from the reach of children.

Figure 4. 15 Plan showing indoor sensor locations in Case Study 3

- **Heat Flux Sensor**

An optimal measurement spot on the limestone block wall of the ground floor of Case Study 1 was selected to install the equipment sensors. On the interior surface of this spot, the heat flux sensor and one of the temperature sensors were put in place using double-sided tape. In contrast, the other temperature sensor was placed on the surface of the exterior wall (Figure 4.16). However, the high indoor temperature on the first floor prevented measurement of the U-value of the concrete block wall of the first floor. This is because the device's operation requirements and ISO 9869-1:2014 standards requires at least a 5°C-10°C temperature difference between the outside and inside to obtain accurate results (ISO 2014). For this reason, the device was installed on the concrete block wall of Case Study 3, which was constructed in the same period and made of the same materials and at the same thickness as Case Studies 1 and 2 and where a five-degree difference between the inside and the outside was achieved. The measurement period of two weeks fulfilled the requirements of the ISO 9869-1:2014 standards with regard to the acceptable deviation between the beginning and the end of measurement in U-value and R-value.

Figure 4. 16 Heat flux sensor installation on both the limestone block wall and hollow concrete block wall

- **Current Clamp Meter and Socket Energy Meter**

Case Study 1

The two floors of the terraced house were built at two different times, and each floor has separate electricity meters. The ground floor has two main electricity meters, and the first floor has only one electricity meter. Hence, three Tinytag clamp meters were installed on the main electricity meters to measure total energy consumption, and two clamp meters were installed on the air conditioning units to measure their energy use for cooling. Socket energy meters were employed to measure the energy consumption of the electric boilers located in the kitchens and bathrooms, as well as to measure the energy consumed by the electrical heaters used for heating in winter. Figures 4.17 - 4.18 show the equipment installation plan in case study 1.

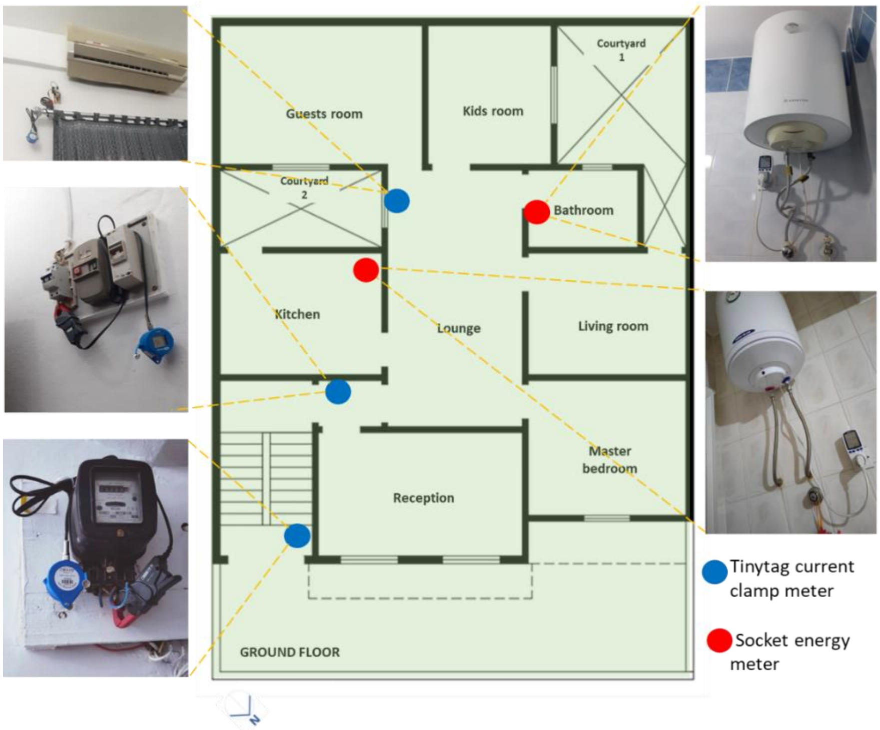


Figure 4. 17 Energy meter location and installation on the ground floor - Case Study 1

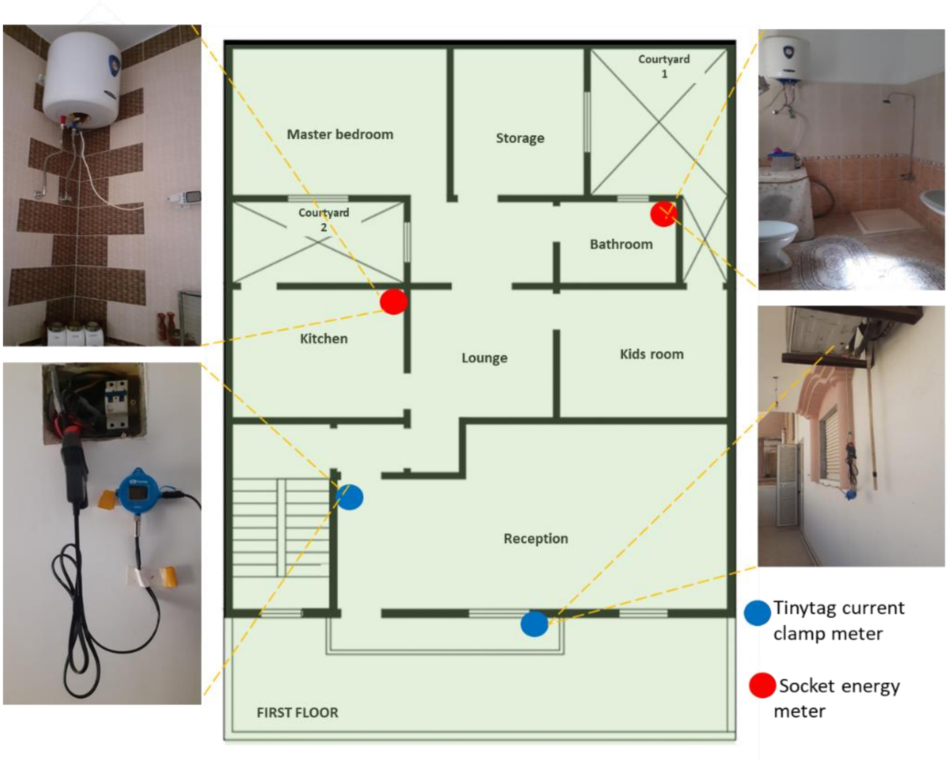


Figure 4. 18 Energy meter location and installation on the first floor - Case Study 1

Case Study 2

To measure the building's energy consumption, a Tinytag clamp meter was installed on the main electricity meter to measure the total energy consumption, and two clamp meters were installed on the air conditioning units to measure their energy use for cooling. Due to the difficulty of installing the Tinytag clamp meters on the other two air conditioners, socket energy meters were used. In addition, to measure the energy consumption of the boilers located in the kitchen, bathroom, and toilet, three socket energy meters were used (Figure 4.19). Socket energy meters were also used to measure the energy consumed by the electrical heaters.

Figure 4. 19 Energy meter locations and installation for Case Study 2

Case Study 3

The monitored apartment has two air conditioners to provide the occupants with cooling in the summer. Therefore, two Tinytag current clamp meters were installed on them to measure their energy use in the summer. Another Tinytag current clamp meter was installed on the main electricity meter to measure total energy consumption. Due to difficulties in installing the socket energy meter on the boilers, energy consumed for hot water was not measured. Socket energy meters were employed to measure the energy consumed by the electric heaters in winter (Figure 4.20).

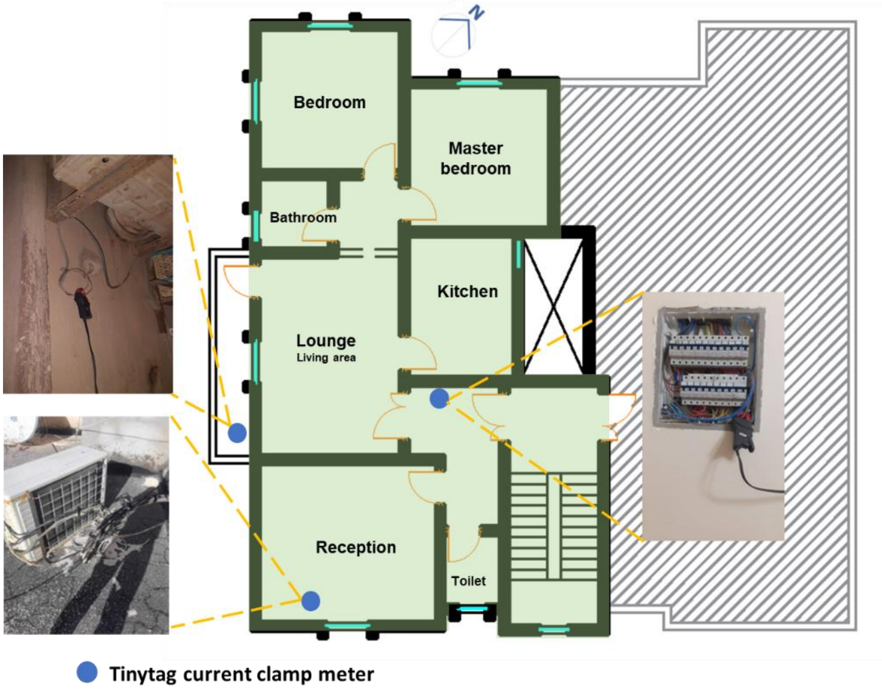


Figure 4. 20 Energy meter locations and installation for Case Study 3

4.2.3 Building Energy Modelling and Simulation

Building energy modelling and simulation are conducted in this research to explore the energy-saving potential of retrofitting existing residential buildings in Benghazi in Libya. DesignBuilder software is the first and most complete program to create a graphical interface for an EnergyPlus dynamic thermal simulation engine. The software forms a unique tool for assessing building conditions which generates a virtual environment in which building conditions and systems are assessed with different retrofit measures (Chowdhury et al. 2007). DesignBuilder has been chosen for many studies as it offers flexible geometry input and extensive material libraries and load profiles (Boafo et al. 2015; An-Naggar et al. 2017; El-Darwish and Gomaa 2017). Therefore, DesignBuilder, as an EnergyPlus based software tool, is used for model simulation to achieve the current study's aim.

DesignBuilder simulation software was employed in this study to model the Case Study buildings to assess the energy and thermal performance of the base case models. It was then used to study the effect of different energy retrofit measures (ERMs) on building energy performance, as well as to investigate the potential for meeting the requirements of net zero energy buildings. However, to ensure that the simulated building models closely match the real buildings, and to boost the accuracy of the simulation and optimisation results, the building models were first calibrated. The following subsections cover in further detail the building modelling, calibration and optimisation approaches that are adopted in this research.

4.2.3.1 Simulation Plan

Before conducting a simulation, a plan must be created to determine the stages that the researcher should follow to achieve the desired objectives. The simulation plan in this research comprises three phases, as illustrated in Figure 4.21.

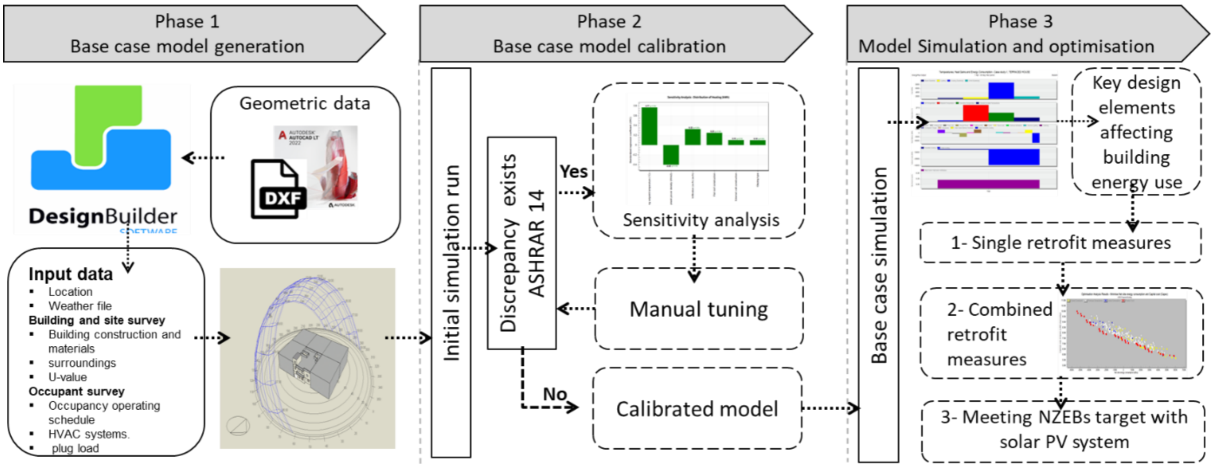


Figure 4. 21 Simulation plan (Author 2022)

4.2.3.1.1 Phase 1: Setting Up the Models

The models of the case study buildings were created in DesignBuilder v7.0.2. 6. Two-D architectural drawings were generated based on the geometric data for the case study buildings, using Auto CAD software 2021 v R.47.0.0. The drawings were saved as a DXF file and then exported to DesignBuilder software. The accuracy of input data has a significant impact on how accurately the simulation process anticipates output. Therefore, it was important to collect as much data as possible in order to avoid making assumptions in the model setting which would consequently impede model calibration and threaten the reliability of the simulation outcomes.

Weather File

The weather files database in DesignBuilder does not include weather information for Benghazi. Hence, an EnergyPlus weather file (EPW) for Benghazi was imported to DesignBuilder to conduct the simulation studies. However, to properly calibrate the building model and for accurate simulation results, the file was modified for the whole year by inserting actual weather data collected during the monitoring period. The EPW file was firstly converted to a CSV file using the EnergyPlus Weather

Statistics & Conversions tool and then modified with actual data, including temperature, humidity, wind direction, wind speed, and atmospheric pressure. The horizontal solar radiation data collected by the solar radiation detector were compared with the TMY weather file to ensure solar radiation data was close to the measured data. The solar radiation data in the EPW file was in good agreement with the measured data. Therefore, solar radiation data in the EnergyPlus weather files were left unchanged. The modified CSV file was then used to create a new EPW file using the same conversion tool.

- **Input Data (building data, occupancy and operation)**

Building information needed to create the models and run the simulation process was entered, such as the building's location, orientation, design, shape and layout, building construction and materials, thermal zones, HVAC systems, lighting power density, and plug loads. The schedule of occupancy was modified based on the data collected during site visits. Information about equipment schedule and the number of people in each room was also modified to represent the real behaviour of the house users. The building information setting in DesignBuilder can be found in Appendix B. The thermo-physical characteristics (U-value) of the building materials were set based on real measurements for wall constructions. A U-value of 2.27 W/m²K was measured for the limestone block wall, and a U-value of 2.61 W/m²K was recorded for the hollow concrete block wall. The U-value of the roofs and floors was determined from DesignBuilder library data. Appendix C provides the results of the heat flux measurements for both limestone block wall and hollow concrete block wall. Moreover, since the study did not include measurement of the infiltration rate, the infiltration rate was set to 6.14 ach based on the average air leakage at 50 Pa of pressure difference for 20 tested dwellings located in the Mediterranean region, with comparable weather conditions and construction to dwellings in Benghazi (Raafat et al. 2023). Table 4.10 summarises the adopted settings and conditions for the simulation process.

Table 4. 10 Summary of main simulation settings

Parameters	**Setting**			**Reference**
	Case study 1	**Case study 2**	**Case study 3**	
External conditions	Mid-latitude Steppe and Desert Climate "Bsh", Benghazi			Energy plus
Orientation	NE	NW	SE	Surveyed
Floor area m²	GF 147m²	230 m²	1200 m², 150 m² each flat	Surveyed
	FF 152m²			

Building material		As defined in Table 4.2		Surveyed
Occupants	5 people in each floor	5 people	5 people in the monitored flat	Surveyed
Occupancy Density				
Ground floor	0.034(people/m²)	0.022(people/m²)	0.033(people/m²)	Calculated
First floor	0.033 (people/m²)			
Fabric parameters				
Limestone block wall U-value	2.27 w/m²K			Measured
Hollow concrete block wall U-value	2.61 w/m²K	2.61w/m²k	2.61w/m²k	Measured
Roof -U value	3 .09 W/m²K	2 .05 W/m²k	2 .05 W/m²k	Calculated/DB
Floor U-value	1.5 W/m²K	1.5 W/m²k	1.5 W/m²k	Calculated/DB
Windows g-value	0.8(80%)	0.8(80%)	0.8(80%)	DB
Windows U-value	5.7	5.7	5.7	DB
Window to Wall ratio	15%	20%	10%	Calculated
Window glazing	6m single layer clear glass with no solar protection	6m single layer clear glass with no solar protection	6m single layer clear glass with no solar protection	Surveyed
Infiltration rate at 50 Pa infiltration rate	6.14 h^{-1}	6.14 h^{-1}	6.14 h^{-1}	Estimated from literature review
DHW	Electric Water heaters	Electric Water heaters	Electric Water heaters	Surveyed
Lighting	LED lighting	LED lighting	LED lighting	Surveyed
HVAC system				
Cooling	**GF**: One split AC unit in the lounge **FF**: One split AC unit in the reception	4 split AC units located in (lounge, reception, living room, master bedroom)	One Split AC unit in the lounge, and one split AC unit in the reception.	Surveyed
Heating	GF: 1 electric heater (living room) FF: 3 electric heaters (lounge-kids' room-reception)	3 electric heaters (Master Bedroom - Bedroom1-Bedroom2)	2 electric heaters (Master Bedroom - Lounge)	Surveyed

Ventilation	Natural	Natural	Natural	Surveyed
Heating set point-setback	GF 24 °C – 20°C FF 29°C – 20 °C (Kids room) FF 27°C – 20 °C (Lounge) FF 25°C – 20 °C (Reception)	26°C – 20°C (Bedroom1) 26°C – 20°C (Bedroom2) 23°C – 20°C (Master bedroom)	23 °C – 20°C (Master bedroom) 23 °C – 20°C (Reception)	Surveyed
Cooling set point/setback	**GF** 24°C – 26°C **FF** 22°C – 24°C	22°C – 25°C	22°C – 25°C	Surveyed
Operation schedule	Weekdays 7:00-9:00 & 14:00-23:00	Weekdays 7:00-9:00 & 14:00-23:00	Weekdays 7:00-9:00 & 14:00-23:00	Surveyed
	Weekends 8:00 - 23:00	Weekends 8:00 - 23:00	Weekends 8:00 - 23:00	
HVAC Operating time	22 hours	22 hours	22 hours	Surveyed

4.2.3.1.2 Phase 2: Model Calibration

The simulation study conducted in DesignBuilder was started by calibrating the case study models. After conducting the initial simulation, the simulation results were compared with the measured energy consumption and indoor zone temperature. The discrepancy between measured and simulated data was calculated based on ASHRAE Guideline 14-2002. The initial calculations showed an unacceptable percentage error between the measurement and the simulation results. For this reason, some parameters of the building model need were tuned manually to bring the percentage of error into the acceptable percentage range as recommended by ASHRAE Guideline 14-2002 (ASHRAE14 2002). To determine these parameters, sensitivity analyses were conducted using cooling load and heating load as the objective functions. The parameters to which the cooling and heating loads were most sensitive to were optimised manually until an acceptable percentage of error between measured data and simulation results were obtained. More information on the sensitivity analysis is provided in the following section. The calibration plan adopted in this research is described in Figure 4.22.

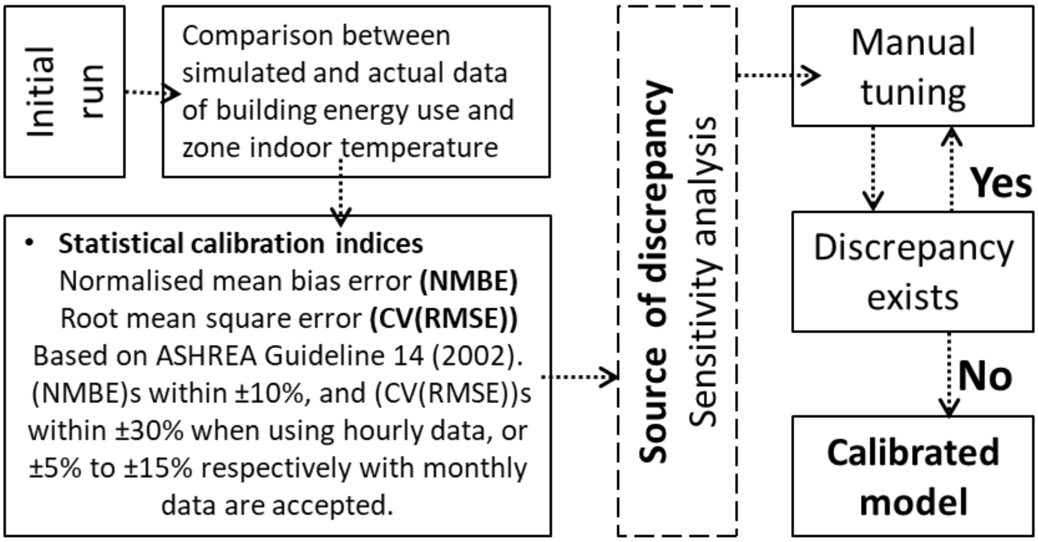


Figure 4. 22 Calibration plan (Author 2022)

- **Energy Consumption and Zone Temperature Calibration**

The discrepancy between measured and simulated building performance based on ASHRAE Guideline 14-2002 used two statistical indices: normalised mean bias error (NMBE); and coefficient of variation of the root mean squared error (CV(RMSE)). Table 4.11 lists the thresholds for NMBE and CV(RMSE) for monthly and hourly data as defined by ASHRAE 14-2002. Both hourly and monthly calibrations were adopted in this research. NMBE and CV(RMSE) indices are calculated through the following formulae, (1) and (2):

$$NMBE = \frac{\sum_{i=1}^{N_i}(M_i - S_i)}{N_i \sum_{i=1}^{N_i} M_i} \times 100 \qquad (4.2)$$

$$CV(RMSE) = \frac{\sqrt{\sum_{i=1}^{N_i}\left[\frac{[(M_i - S_i)]^2}{N_i}\right]}}{\frac{1}{N_i}\sum_{i=1}^{N_i} M_i} \times 100 \qquad (4.3)$$

Where M_i is the actual energy data point during the time interval, S_i is the simulated energy data point during the same time interval, and N_i is the count of the number of values used in the calculation.

Table 4. 11 Calibration criteria, ASHRAE Guideline 14-2002

Calibration criteria	**Index**	**Acceptable error**
Monthly criteria	NMBE	±5%
	CV(RMSE)	±15%
Hourly criteria	NMBE	±10%
	CV(RMSE)	±30%

- **Sensitivity Analysis**

The source of discrepancy in this research was defined through sensitivity analysis, which is an existing feature in DesignBuilder. The sensitivity analysis approach adopted in this research is clarified in Figure 4.23. It begins by determining variations of input parameters (probability distribution), creating a building energy model based on input variations, and then a simulation run. As soon as the simulation results had been collected, sensitivity analysis was carried out to determine the most and least influential parameters. Once these parameters were determined, the values of the least influential parameters were removed from further consideration, decreasing the number of parameters that needed to be adjusted (Reddy et al. 2007), while the most influential parameters were tuned manually until an acceptable level of discrepancy was reached between the measured and simulated data. In this study, the selected objective functions in the sensitivity analysis were cooling and heating loads.

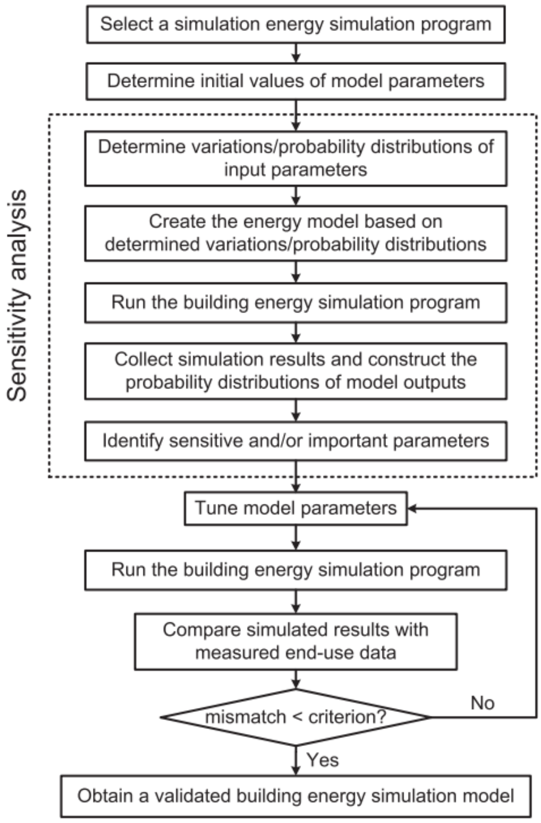


Figure 4. 23 A typical schematic flow diagram for building model calibration using sensitivity analysis (Li et al. 2016)

A primary sensitivity test was conducted on different parameters to assist the calibration phase by identifying the hierarchical order of the sensitive parameters. Once these parameters are determined, the values of the least influential parameters are removed from further consideration, and the most influential ones are tuned manually until an acceptable discrepancy between the monitored and simulated data is achieved. The method applied is regression, where the indicating factor is the standardised regression coefficient (SRC), and the number of random simulations is chosen as 100 times the number of parameters.

4.2.3.1.3 Phase 3: Model Simulation and Optimisation

After verifying the validity of the simulation by obtaining a simple error rate, the models were utilised in running the simulation as base case models, to gain a clear picture of each building's thermal and energy performance. After that, a hybrid optimisation approach combining passive retrofit measures and on-site PV energy generation system was employed to improve the energy efficiency of the case study models. Different passive retrofit measures were first assessed individually (one single measure at a time) to investigate their influence on the cooling and heating loads of each case study building. Then, a combination of these retrofit measures was studied via multi objective optimisation, to determine the optimal energy retrofit solutions in reducing energy consumption without compromising indoor thermal comfort. Then, based on the optimisation simulation results, another simulation study was carried out to investigate the potential for meeting the remaining energy needs through a photovoltaic system.

4.2.4 Case Study Model Optimisation

This section explains the approach to the investigation of retrofitting measures. The theoretical background for the available retrofitting measures was addressed in Chapter 3. Further investigations will be devoted to their application to the case of Libyan dwellings, with increased focus on building envelope parameters as, the main contributors to cooling and heating loads, as defined by sensitivity analysis and heat balance simulation results. Case study model optimisation is centred on the investigation of different retrofit measures for the building envelope, which can be divided into two broad categories: thermal insulation with biobased materials; and solar control. Single and combined retrofit measures were employed to identify the optimal measures in improving the buildings' energy performance without compromising thermal comfort. Further study was conducted to investigate the potential for meeting the energy consumption of the optimised models by installing photovoltaic systems to achieve the requirements of net zero energy buildings. The optimisation simulation plan is described in Figure 4.24.

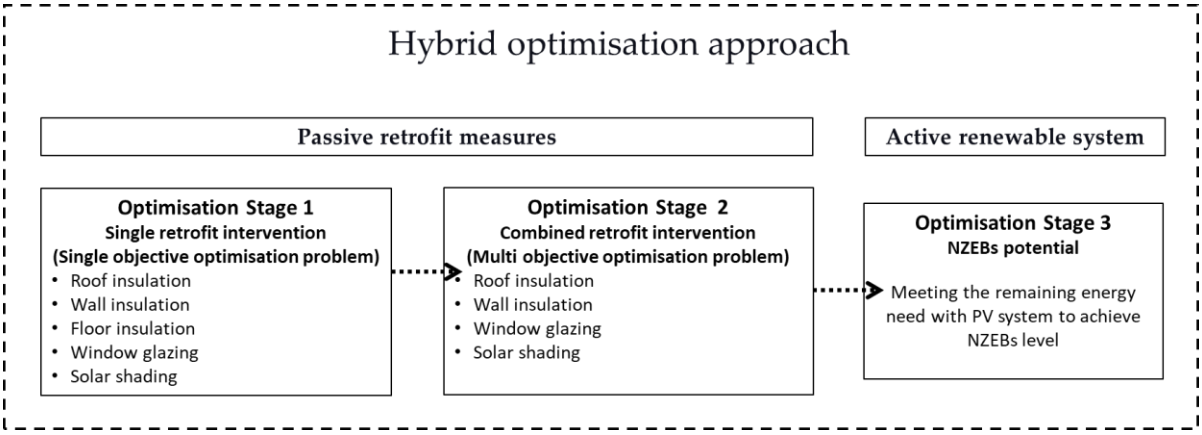


Figure 4. 24 optimisation simulation plan

4.2.4.1 Optimisation Stage One: Single Retrofit Measures

First, each of the following parameters were investigated to find the optimal choices for each single measure in reducing buildings' energy use: roof, floor and wall insulation, glazing system and solar shading.

4.2.4.1.1 Thermal Insulation of Opaque Envelope

This section examines the impact of biobased insulation materials when upgrading the opaque elements of the building envelope. The parameters considered in the study are the location, material, and thickness of the insulation materials. The base case walls and roofs has high U-values leading to increase the heat transfer through them. Thus, insulation materials are added to the walls and roofs to improve their energy efficiency. Different types of biobased based insulation materials with low thermal conductivity and low U-values were applied to the roof and walls to investigate the potential for reducing cooling and heating loads without compromising indoor thermal comfort. U-values selected for optimising the building envelope elements range between 0.5 W/m^{2}K and 0.1 W/m^{2}K at 0.1 decrements. The investigation of insulation effects involves the application of biobased insulation materials, either inside or outside, to decrease the overall U-value of the building envelope. As an attempt to reduce embodied carbon, four biobased insulation materials were selected for the investigation, namely: sheep wool, camel hair, date palm, and hemp fibres. These natural materials can be manufactured inside Libya, especially based on the availability of raw materials for their production. It might not be possible to obtain any one of these materials in the quantities required for large-scale retrofits: however, taken together, these retrofits can be accomplished.

The thermal properties of sheep wool, hemp fibres, and date palm fibres were gathered from previously published research, and manufacturers' construction websites (Latif et al. 2014; Raza et al. 2022). The author measured the thermal conductivity of the camel hair. The measurement methods for thermal conductivity are broadly classified into two categories: transient and steady-state methods. However, achieving a steady-state condition can take time, leading to a longer testing period. So, to reduce the measurement time, transient methods, as a quicker approach, were adopted in this research. The ISOMET 2114 instrument was used for the measurement of the thermal conductivity of the camel hair material (Figure 4.25). The instrument is equipped with two measurement probes: needle probes for intrusive measurement; and surface probes for non-intrusive measurement. For camel hair measurement, the surface probe was used. The sample was placed on the measuring surface of the surface probe. Measurements were taken three times on three different surface areas. Each measurement result was the average of three conductivity readings. It took half an hour to take each reading. The results show that the thermal conductivity of the camel hair sample is 0.043 W/mK. The thermal properties of biobased material employed for materials setup in DesignBuilder are presented in Table 4.12. Table 4.13 summarises the insulation specifications used for the optimisation setup in DesignBuilder, while Table 4.14 shows the thickness of each biobased insulation material required to meet the optimised U-values.

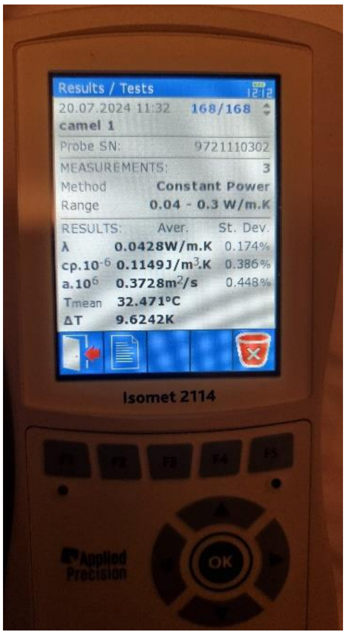


Figure 4. 25 The thermal conductivity of camel hair, measured by ISOMET 2114

Table 4. 12 The thermal properties of biobased insulation materials used for materials setup in DesignBuilder

Material	**Thermal Conductivity W/m K**	**Density kg/m³**	**Specific Heat Capacity J/kg K**
Sheep wool	0.039	19	1700
Camel Hair	0.0428	19	1700
Date palm fibres	0.051	254	1356
Hemp fibres	0.038	50	1700

Table 4. 13 Specifications for biobased insulation materials used to optimise the roof and walls

	Element	**Parameters**		
		Insulation Position	Material	U-Value range W/m² k
Thermal insulation	Roof	External-internal	Sheep wool, Camel hair, Date palm, Hemp fibres	0.5-0.1 @ 0.1 decrement
	Wall	External – internal	Sheep wool, Camel hair, Date palm, Hemp fibres	0.5-0.1@ 0.1 decrement
	Ground floor	Internal	Sheep wool, Camel hair, Date palm, Hemp fibres	0.5-0.1 @ 0.1 decrement

Table 4. 14 The thickness of each biobased insulation material to meet the optimised U-values (DesignBuilder library)

			Optimised U-value (W/m²K)				
			0.5	0.4	0.3	0.2	0.1
Upgrading the roof (Case study1) Base case U-value: 3.09(W/m²K)	Sheep wool	Insulation thickness (m)	0.0626	0.0821	0.1146	0.1796	0.3746
	Camel hair	Insulation thickness (m)	0.0642	0.0842	0.1175	0.1842	0.3842
	Date palm fibres	Insulation thickness (m)	0.0799	0.1054	0.1479	0.2329	0.4879
	Hemp fibres	Insulation thickness (m)	0.0610	0.0800	0.1117	0.1750	0.3650
Upgrading the roof (Case Studies 2 & 3) Base case U-value: 2.05 (W/m²K)	Sheep wool	Insulation thickness (m)	0.0590	0.0785	0.1110	0.1760	0.3710
	Camel hair	Insulation thickness (m)	0.0605	0.0805	0.1138	0.1805	0.3805
	Date palm fibres	Insulation thickness (m)	0.0756	0.1006	0.1423	0.2256	0.4756
	Hemp fibres	Insulation thickness (m)	0.0575	0.0765	0.1081	0.1715	0.3615
Upgrading the limestone block wall Base case U-value: 2.27 (W/m²K)	Sheep wool	Insulation thickness (m)	0.0581	0.0776	0.1101	0.1751	0.3701
	Camel hair	Insulation thickness (m)	0.0596	0.0796	0.1129	0.1796	0.3796
	Date palm fibres	Insulation thickness (m)	0.0760	0.1015	0.1440	0.2290	0.4840
	Hemp fibres	Insulation thickness (m)	0.0566	0.0756	0.1073	0.1706	0.3606
Upgrading the concrete block wall Base case wall U-value: 2.61 (W/m²K)	Sheep wool	Insulation thickness (m)	0.0611	0.0806	0.1131	0.1781	0.3731
	Camel hair	Insulation thickness (m)	0.0627	0.0827	0.1160	0.1827	0.3827
	Date palm fibres	Insulation thickness (m)	0.0799	0.1054	0.1479	0.2329	0.4879
	Hemp fibres	Insulation thickness (m)	0.0596	0.0786	0.1102	0.1736	0.3636
Upgrading the ground floor Base case wall U-value: 1.5 (W/m²K)	Sheep wool	Insulation thickness (m)	0.0611	0.0806	0.1131	0.1781	0.3731
	Camel hair	Insulation thickness (m)	0.0627	0.0827	0.1160	0.1827	0.3827
	Date palm fibres	Insulation thickness (m)	0.0799	0.1054	0.1479	0.2329	0.4879
	Hemp fibres	Insulation thickness (m)	0.0596	0.0786	0.1102	0.1736	0.3636

4.2.4.1.2 Glazing System

In the examination of window systems, energy-efficient glazing replaced the existing glazing type to study the impact of both U-value and solar factor (g-value) on energy saving and enhancement of the indoor thermal environment. Based on DesignBuilder library data the thermal transmittance of the existing single-glazing windows in all case study buildings is 5.78 W/m²K, and the solar factor is 0.8. From DesignBuilder library, different glazing types are examined including six double glazing and three triple glazing types that have different thermal and solar properties as described in Table 4.15. Energy-efficient glazing types that significantly reduce light transmission were excluded from the optimisation stage.

Table 4. 15 Glazing type used for window optimisation (DesignBuilder library)

		Glazing type	**U-value W/m². K**	**Solar Transmission SHGC**	**Light Transmission**
Base case		Sgl Clr 6mm	5.78	0.8	0.88
Double glazing	**Dbl 1**	Dbl Clr 6mm/13mmAir	2.66	0.7	0.78
	Dbl 2	DblClr/6mm/13mmArg	2.5	0.7	0.78
	Dbl 3	Dbl LoE Clr 6mm/13mm Arg	1.5	0.56	0.75
	Dbl 4	Dbl Ref-D Clr 6mm/13mm Air	2.65	0.426	0.3
	Dbl 5	Dbl Ref-D Clr 6mm/13mm Arg	2.49	0.426	0.3
	Dbl 6	Dbl Ref-D Tint 6mm/13mm	2.65	0.359	0.23
	Dbl 7	Dbl Ref-D Tint 6mm/13mm Arg	2.49	0.359	0.23
Triple glazing	**Trp 1**	Trp Clr 3mm/13mm Air	2.1	0.68	0.74
	Trp 2	Trp Clr 3mm/13mm Arg	1.6	0.68	0.74
	Trp 3	Trp LoE Clr 3mm/13mm Arg	0.78	0.47	0.66

4.2.4.1.3 Solar Shading

Solar shading in hot climates plays an important role in improving indoor thermal comfort and reducing energy use. Sensitivity analysis results reveal that shading has a moderate impact on cooling load and heating load, which can be attributed to the small window-to-wall ratio (WWR). Shading can improve thermal comfort in the summer: however, adding deep overhangs can negatively affect the quality of day lighting and thermal comfort in the winter, Consequently, deep overhangs and side fins above one metre in depth were excluded. See Table 4.16 for local shading specifications used for model optimisation in DesignBuilder.

Table 4. 16 Shading optimisation parameters

Base case	No shading					
Optimisation case	Overhangs, Depth m	Side fins+ overhangs, Depth m	Side fins	Louvers		
N Shading	0.3-0.5-1	0.3-0.5-1	0.3-0.5-1	Depth	Spacing	Angle
				30	30	15°
E Shading	0.3-0.5-1	0.3-0.5-1	0.3-0.5-1	Depth	Spacing	Angle
				30	30	15°
W Shading	0.3-0.5-1	0.3-0.5-1	0.3-0.5-1	Depth	Spacing	Angle
				30	30	15°
S Shading	0.3-0.5-1	0.3-0.5-1	0.3-0.5-1	Depth	Spacing	Angle
				30	30	15°

4.2.4.2 Optimisation Stage Two: Combined Retrofit Measures

Combined retrofit measures were also investigated via multi-objective optimisation tool (Pareto optimisation method) in DesignBuilder in order to identify the optimal compromise between several independent parameters to establish a range of solutions for optimising two conflicting objectives. In this approach, all objectives are given the same weight, with the aim of achieving a compromise between these objectives. This results in a set of trade-off solutions that, when plotted, form a curve known as the Pareto front, in which the objectives perform better than any other point above that curve (Huws and Jankovic,2014). Moving along the Pareto front curve, all of the optimal trade-off solutions for the multi-objective problem can be found. Pareto front optimisation offers continuous and iterative modification of the building model. The genetic algorithm (GA) technique was used to optimise the design parameters identified through sensitivity analysis. In this research, the parameters that are selected for the optimisation are created in DesignBuilder. The selected parameters are the parameters of the external walls, roof, shading, and glazing as illustrated in tables 4.14, 4.15, and 4.16. The two objective functions selected are 'minimising total site energy consumption' and 'minimising thermal discomfort'. Primary cooling and heating energy demand are additional outputs that are added in the optimisation setting for further analysis. By examining the Pareto front, the solutions that reduce energy consumption without worsening indoor thermal comfort are found.

4.2.4.3 Optimisation Stage Three: Investigate the Potential for Meeting the Requirements of Net Zero Energy Buildings (NZEBs)

The effectiveness of on-site energy generation to meet remaining energy demand through renewable energy (a PV system) was investigated. Set up of the photovoltaic performance model in DesignBuilder started with the development of a geometric model for the solar PV array for installation on the building model roof, facing toward the south to allow the maximum amount of sunlight to be received by the panels. The second step was the assignment of photovoltaic electrical performance models to the solar PV array. Electrical performance models were then created within the DesignBuilder library, using actual manufacturer specifications. Most residential solar panels on today's market are rated to produce between 250 and 400 watts per hour. In this research, 400W PV panels (2 X 1 m, with standard 72 cells) were created facing south on the roof of each model to produce electricity. Walking spaces between the PV panels for service and maintenance purposes were considered. The solar panels were firstly tilted at several angles to determine the yearly optimal tilt angle. The PV panels were then angled at 30°, as this showed the highest annual energy production. This finding corresponds with the results of two studies conducted to provide a proposal for installing a photovoltaic plant in Cairo in Egypt: a city Located at a latitude of 30.1°, which is close to the latitude of Benghazi (32.11°) (Albadry et al. 2017; El Abagy et al. 2021). Setup of the PV systems was completed by including an electrical load centre to model direct current (DC) to alternating current (AC) inverter equipment. See Appendix D for PV manufacturer specifications and PV performance model setup in DesignBuilder.

4.3 Data analysis

To achieve the aim of the study, a research approach combining case study monitoring and numerical simulations was adopted. The data collected through monitoring the case study buildings were used to obtain an overall view of each building's thermal and energy performance, as well as to create and calibrate the building model. To understand indoor environmental conditions, a statistical method was adapted to analyse the data. The maximum, minimum, and mean indoor temperature of all indoor spaces across all seasons of the year were determined, to be assessed against thermal comfort limits identified by ASHRAR 55 for summer, winter and transition seasons. The measured data for energy consumption for each category during summer and winter was studied to determine which category consumed the most energy and presented greatest potential for energy conservation. Based on the initial data analysis results, the buildings consume the most energy for cooling and heating purposes. Accordingly, cooling and heating load were allocated as an objective function in the sensitivity analysis to determine the most influential design parameters on building energy consumption using DesignBuilder software.

The data collected was also used for model setting and for model calibration, for which monthly and hourly energy consumption and zone indoor temperatures were compared to simulated data based on ASHRAE 14 to reduce the discrepancy between these values. After calibrating the case study buildings model, the study also involved parametric analyses to examine the influence of different retrofit measures on building energy and thermal performance. To achieve the greatest building energy reduction, a combination of these passive strategies has been investigated to identify the optimal design solution, that produced the highest energy savings with an acceptable range of comfort hours. The optimal solutions are assessed against the Passivhaus targets for retrofits. Following building optimisation stages using passive retrofit measures, a further study was carried out to investigate the effectiveness of integrating a PV system to meet the remaining energy demand of the buildings and reach the net zero energy buildings (NZEBs) target.

4.4 Chapter Summary

This chapter has presented the methodology adopted in this research. The research approach selected to accomplish the research aim combines thermal performance and energy consumption monitoring for the case study buildings, as well as numerical simulations based on computer models in DesignBuilder software. The first section of this chapter explained the method of case study selection, clarifying the reasons for choosing specific buildings for investigation and describing their main features. The second section illustrated the monitoring protocol and provided a description of the monitoring equipment. The procedure followed to install the devices, and their number and location were also described. In the third section, the case study modelling and simulation approach was discussed. This section was divided into three phases: phase (1) presented the process of setting up the models; phase (2) provided the method adopted in this research to calibrate the building models; and phase (3) described the approach adopted to investigate the potential for improving the energy efficiency of the case study buildings via hybrid optimisation approach.

Chapter 5: Buildings Monitoring Study - Results and Discussion

5.1 Introduction

In this chapter, an initial analysis of the collected data is carried out to provide the details of the energy performance and indoor thermal conditions of the case study buildings. This chapter first evaluates the current state of indoor thermal conditions of the three case study buildings based on ASHRAE standards 55-2017 for summer, winter, and the transitional seasons. Statistical methods are employed for the analysis and interpretation of the data. Firstly, the maximum, minimum, and mean indoor temperatures of all indoor spaces are determined to evaluate their thermal condition based on the comparison with the upper and lower bands of the thermal comfort. Secondly, measured data of energy consumption for each category during summer and winter is studied to determine which category consumed energy the most and has higher potential for energy conservation. The findings of the building monitoring study are used later in Chapter 6 for the calibration of the case study models.

5.2 Case Study 1

5.2.1 Indoor Thermal Conditions

Indoor temperature performance is statistically evaluated based on minimum, maximum, and hourly mean values over the observational period. The adaptive comfort standards in ASHRAE 55-2017 is used to increase the tolerances for assessing the thermal comfort (ASHRAE55 2017). The upper and lower bands of comfort temperatures in all seasons are determined using the following equations:

Upper 80% acceptability limit (°C) = 0.31 t mean temp(out) + 21.3 (1)

Lower 80% acceptability limit (°C) = 0.31 t mean temp(out) + 14.3 (2)

Based on this guide, a comfortable air temperature ranges between 22°C to 30°C for summer, 19°C to 26°C for winter, and 21°C to 28°C for transition seasons.

5.2.1.1 During a Summer Month

Based on the statistical analysis, indoor temperature over the summer monitoring period on the ground floor is considered 100% comfortable, and 60% uncomfortable on the first floor when compared with upper and lower bands of thermal comfort of the summer season (Figure 5.1). The mean indoor temperatures of all ground floor spaces fall within the comfort zone except for the bathroom which is naturally ventilated. The lounge, where the air conditioning is located, has the lowest temperatures, while the highest mean temperatures are recorded in the reception which has more wall exposure (ratio of surface) to outdoor conditions. On the other hand, the mean indoor temperatures of most of the first-floor spaces are uncomfortable and lie above the comfort zone which ranges from 22°C to 30°C, excluding the reception where the air conditioning is located.

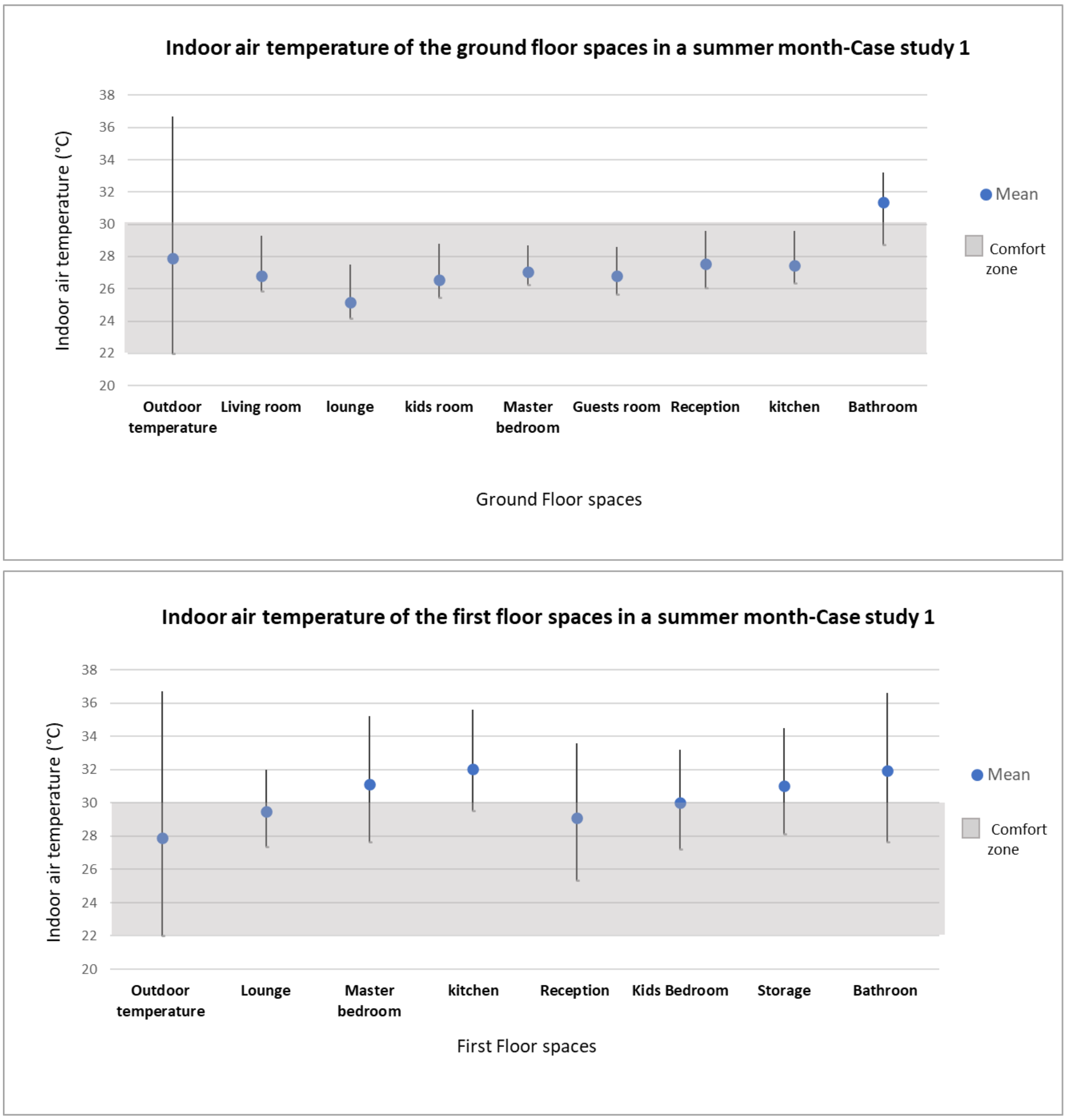
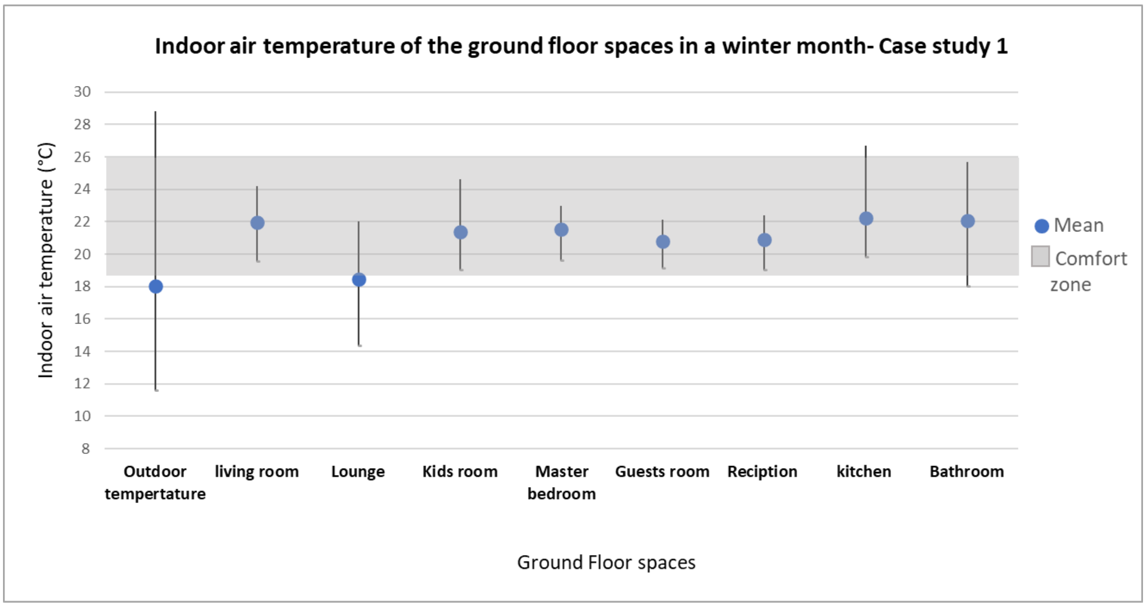


Figure 5. 1 Comparison of the maximum, mean, and minimum indoor temperature values between ground floor and first floor spaces (summer)

5.2.1.2 During a Winter Month

Based on ASHRAE standards 55-2017, a comfortable indoor air temperature in the winter ranges between 19°C and 26°C. No heating devices are used on the ground floor except for the living room where the electrical heater is used for limited days (only for four out of 30 days) of the monitoring period. However, indoor temperatures are comfortable on the ground floor except for the lounge due to its location which remains cool as it does not receive heat from the sun during the day. The mean indoor temperatures of the main spaces on the first floor are also situated within the comfort bands due to the use of the electrical heaters. However, the master bedroom and bathroom are uncomfortable as no heating devices are used (Figure 5.2).



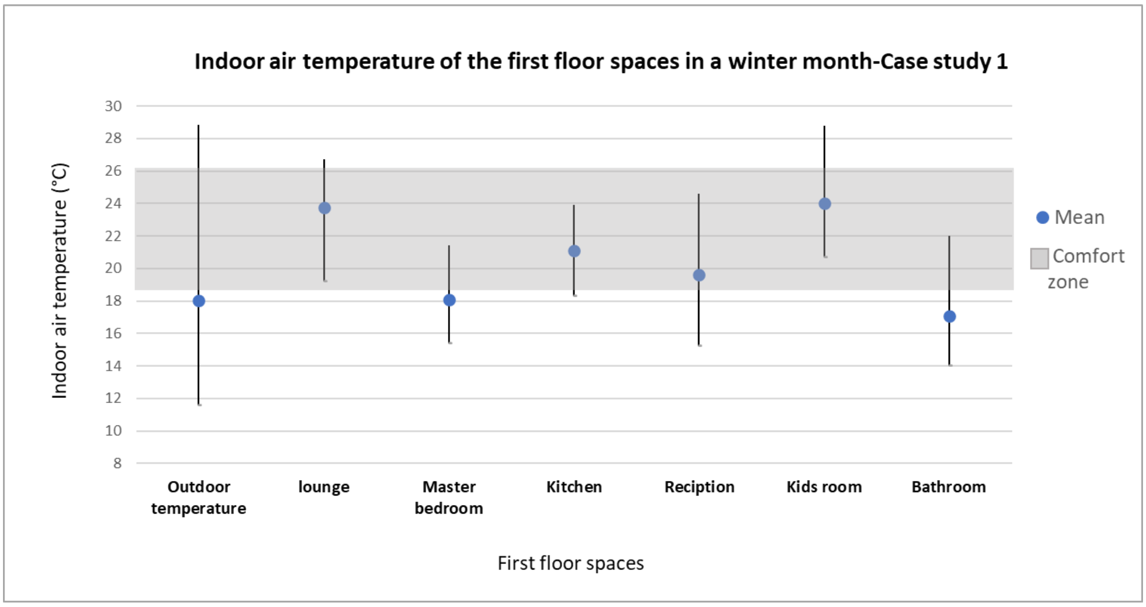
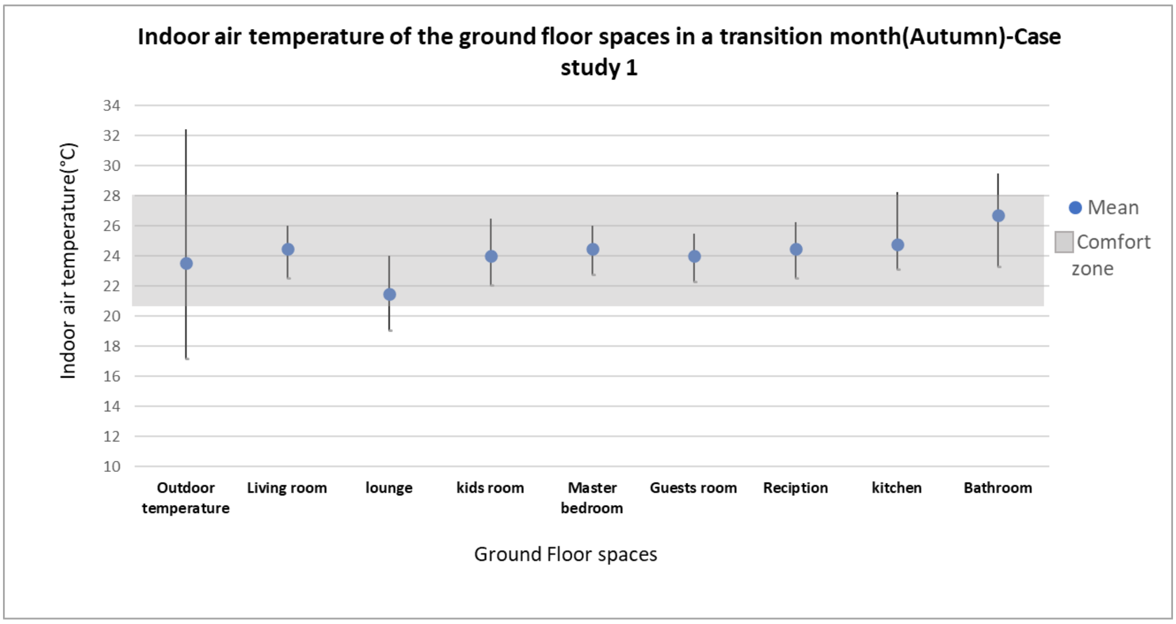


Figure 5. 2 Comparison of the maximum, mean, and minimum indoor temperature values between ground floor and first floor spaces (winter)

5.2.1.3 During a Transition Month

In the autumn months when no heating and cooling devices are used, the mean indoor temperatures of all ground floor rooms fall within the comfort zone band which ranges between 21°C and 28°C (Figure 5.3). Similarly, all first-floor spaces are comfortable where the mean indoor temperature of all spaces falls within the comfort zone bands.



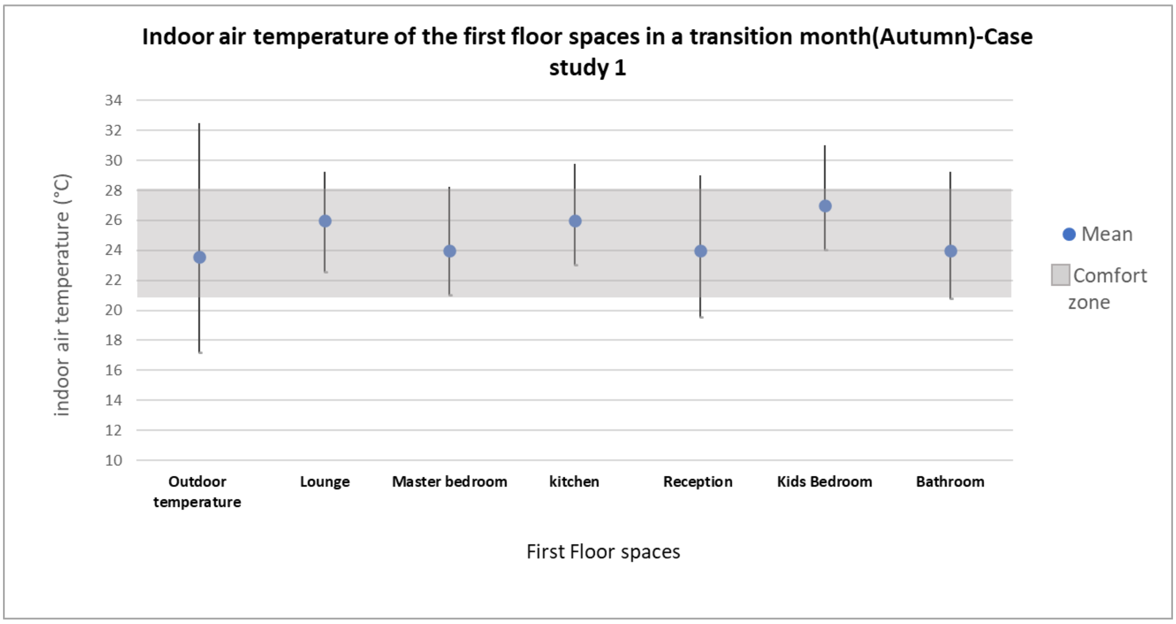


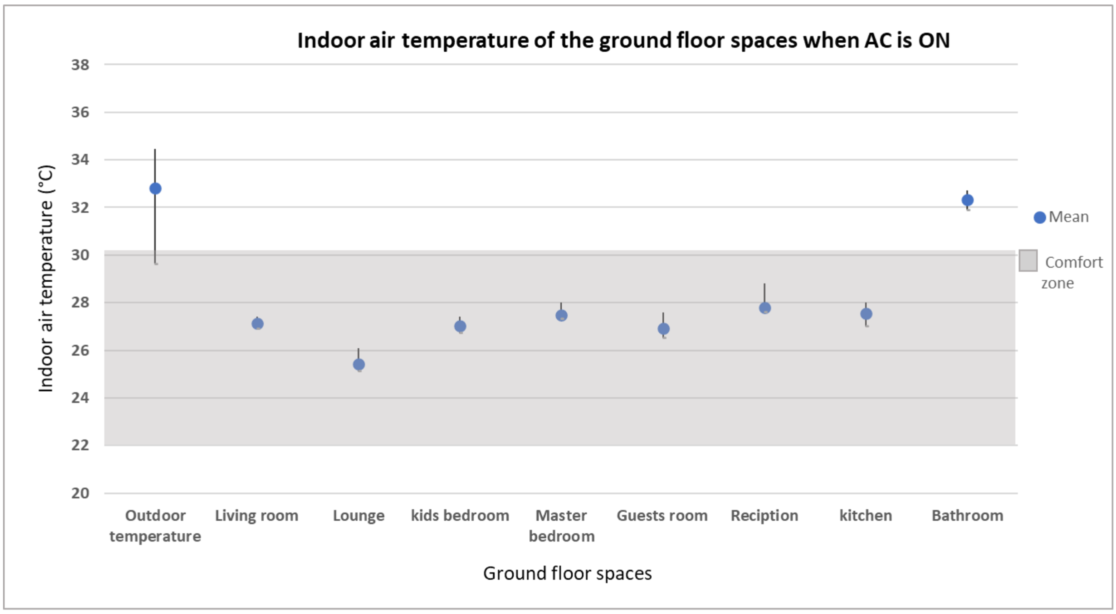
Figure 5. 3 Comparison of the maximum, mean, and minimum indoor temperature values between ground floor and first floor spaces (transition month)

5.2.1.4 Indoor Temperature Performance When Air Conditioner is On and Off

The researcher took advantage of the times when there was a blackout to assess the indoor temperature performance of the building without the air conditioning. To achieve this, two days from the summer observation period were selected. One day when the electricity was cut off during the daytime and the other day when the air conditioning was running, and both days had similar outdoor temperature ranges. On the 6th of July 2022, there was a blackout between 08:30 and 19:30. The indoor temperatures of all spaces were selected and compared with those of comparable hours between 08:30 and 19:30 on the 29th of June 2022 when the electricity was running.

5.2.1.4.1 Ground Floor Spaces

It can be observed in Figure 5.4 that when the air conditioning is off, the mean indoor temperatures in all ground floor spaces fall within the comfort limits. Based on ground floor occupants, all windows and doors are kept closed during the daytime until 17:00 in the afternoon even when the air conditioning is off during blackout and opened to benefit from night cooling when the outside temperature drops at sunset. On the other hand, when the air conditioning is on, only a 1°C reduction in indoor temperature is observed. The lounge, where the air conditioning is located, has the lowest temperature, while the reception with the longest wall surface shared with the outside has the highest air temperature.



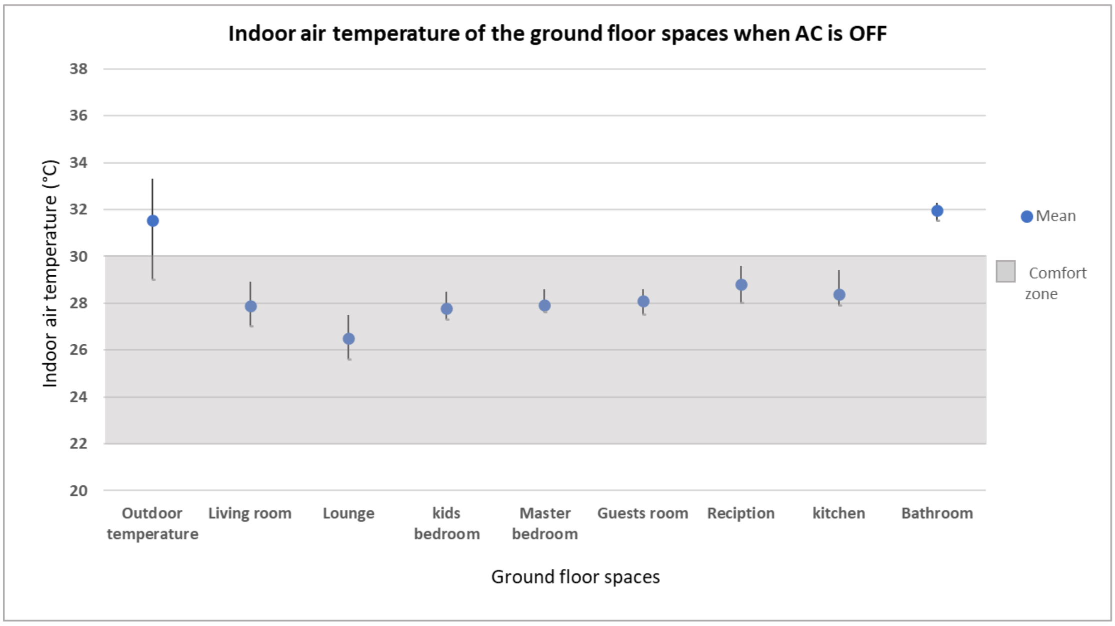
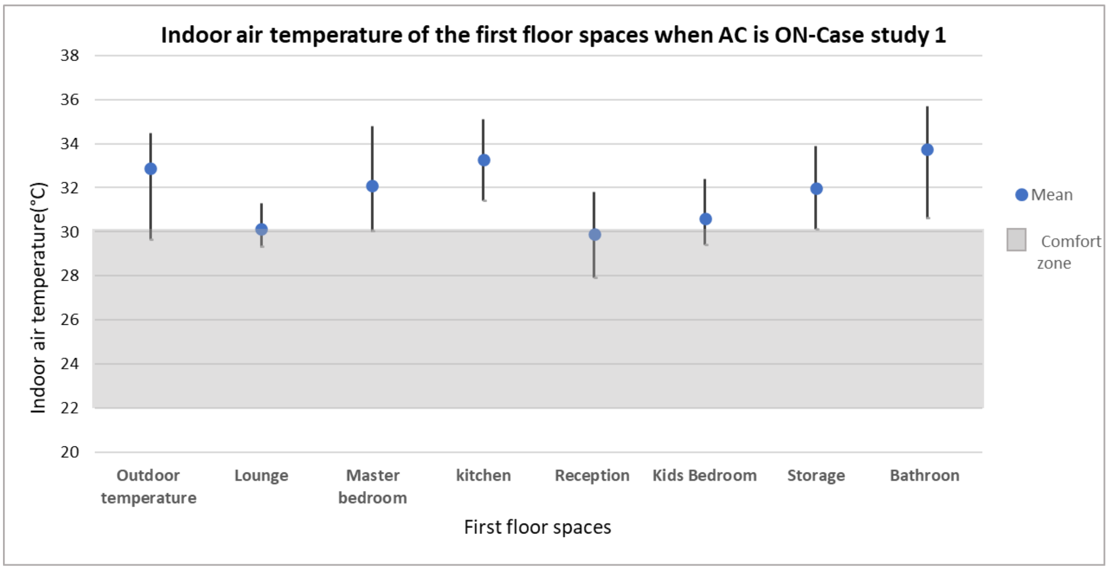


Figure 5. 4 The maximum, mean, and minimum indoor temperature values of ground-floor spaces when air conditioner is ON and OFF

5.2.1.4.2 First Floor Spaces

As illustrated in Figure 5.5, whether the air conditioning unit is running or not, the mean indoor temperatures of all first-floor spaces are uncomfortable and fall above the comfort zone bands, and no drop is noticed when the air conditioning is turned on, including in the reception where the air conditioning is located. Since the walls of the first floor are mostly adjacent to the neighbours, the only explanation for the difference in indoor temperature between the ground floor and first floor is heat gain from the roof. As a result, one air conditioning unit (7.0kW) is not sufficient to bring indoor temperatures of first floor spaces to a comfortable level, and more air conditioning units working more efficiently are needed to provide the residents on the first floor with thermal comfort during summertime.



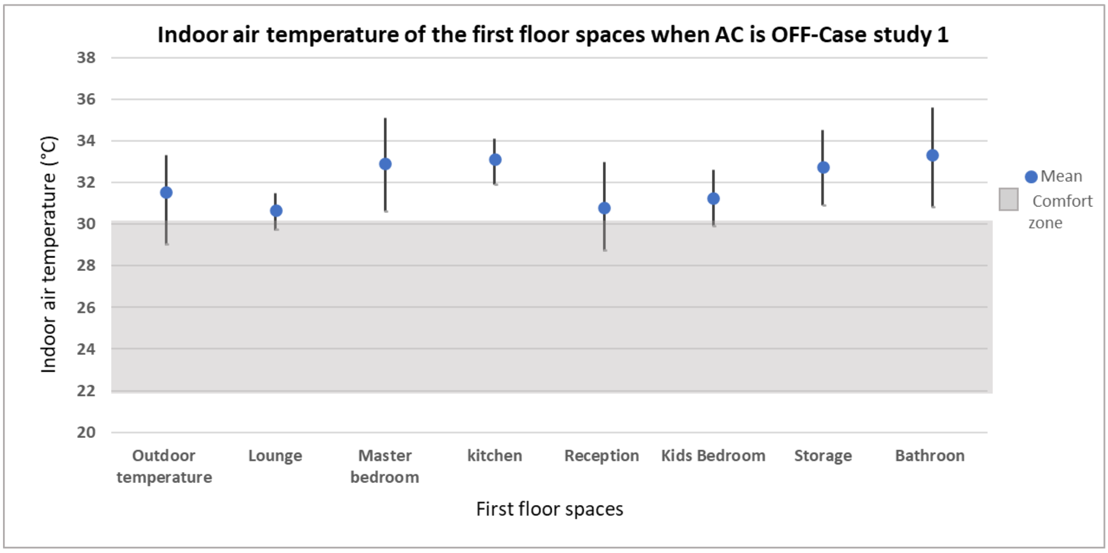


Figure 5. 5 The maximum, mean, and minimum indoor temperature values of first-floor spaces when air conditioner is ON and OFF

5.2.2 Energy Consumption

The monthly energy consumption of case study 1 as illustrated in Figure 5.6 shows that the building consumes the most energy in the summer months, August, and July, followed by September and June. January and February are the months when the building consumes the most energy during the winter. April, October, and November witnesses the lowest energy use as there is no need to operate the cooling and heating systems during these months.

Based on energy consumption measurements in one summer month between 8th June 2022 and 7th July 2022 (Figure 5.7), the ground floor consumed 1317.51 kWh of which 79 % was used for cooling, while for domestic hot water, the building consumed 6 % of the total energy. The remaining 15 % of energy consumption is attributed to lighting & electrical appliances. During the same period, the first floor consumed about 980.45 kWh. The energy used for cooling constituted about 66.9 % of the total energy consumption. Domestic hot water, lighting, and electrical appliances made up 13.15 %, and 19.95 % of consumed energy, respectively. In the summer, the building in total consumed 2297.96 kWh, most of which went toward cooling at 73.9 % of the total used energy. Accordingly, cooling load reduction has a great potential for energy conservation.

The breakdown of energy consumption in one winter month between 12th December 2022 and 10th January 2023 in Figure 5.8 demonstrates that the building consumed 1970.84 kWh for both floors, with about 59.55 % of the energy being used for heating. However, the first floor consumed more energy for heating than the ground floor. In comparison to the first floor, ground floor spaces are more thermally comfortable in wintertime which can be clearly deduced from the limited amount of energy used for heating compared to the first floor. Domestic hot water accounted for 33.7% of the total energy consumption followed by lighting and other appliances which consumed the lowest energy at 6.75%. Consequently, most of the energy consumed by the building in the winter was on heating. Therefore, reducing the heating load must be a primary objective in order to lower building energy consumption.

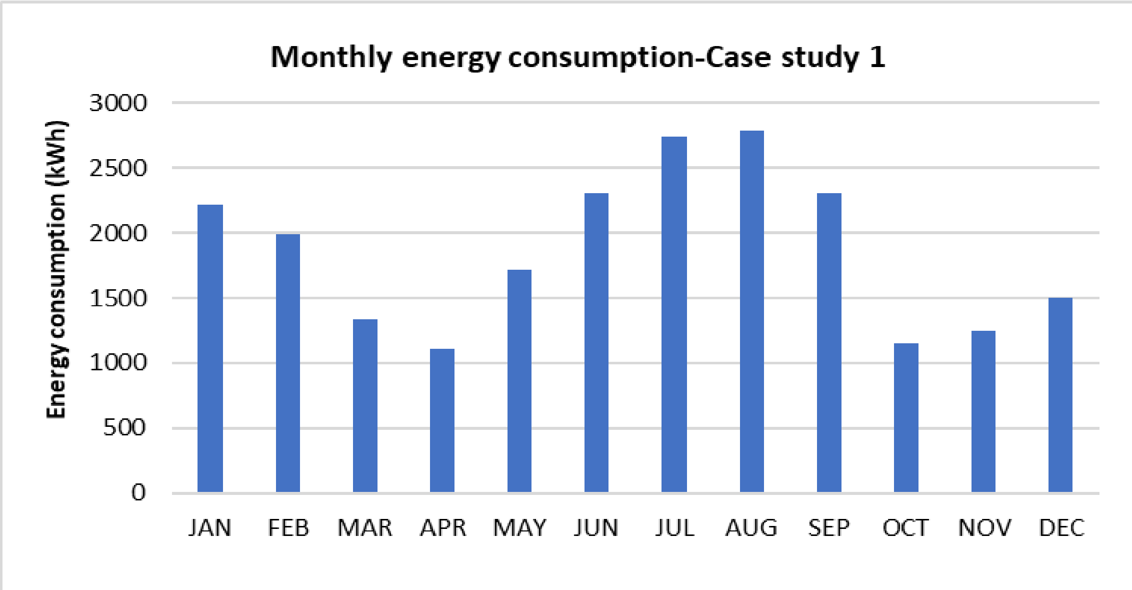


Figure 5. 6 Monthly energy consumption from 8th June 2022 to 7th June 2023

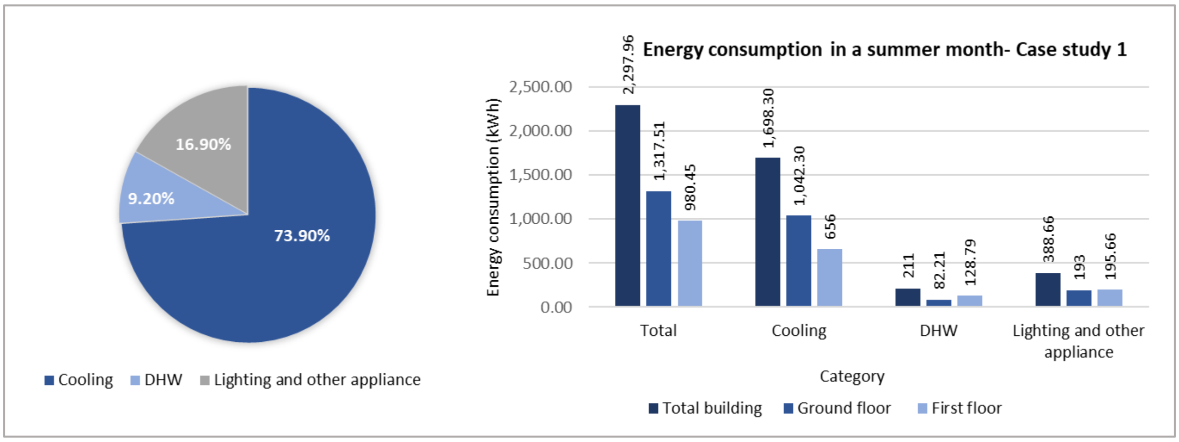


Figure 5. 7 Breakdown of energy consumption of Case Study 1- Summer

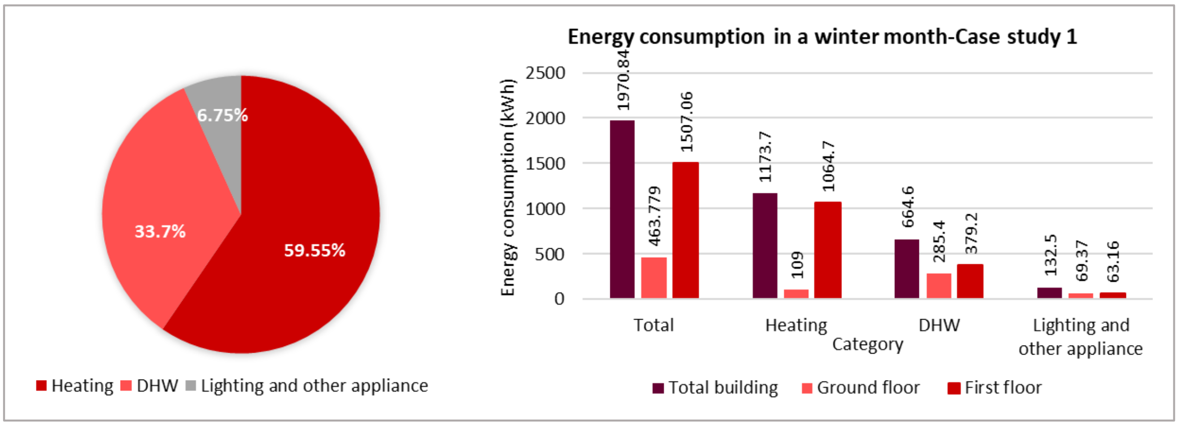


Figure 5. 8 Breakdown of energy consumption of Case Study 1- Winter

5.3 Case Study 2

5.3.1 Indoor Thermal Conditions

5.3.1.1 During a Summer Month

As shown in Figure 5.9, the mean indoor temperatures of all indoor spaces fall within the comfort limits. The lounge, reception, master bedroom, living room, and kitchen where the air conditioning units are located, have the lowest mean air temperatures. The mean indoor temperatures in other spaces where no air conditioning units were installed are higher and considered uncomfortable. This indicates that due to the absence of insulation material, the heat gain through the roof and walls is greater than what the air conditioning system can remove.

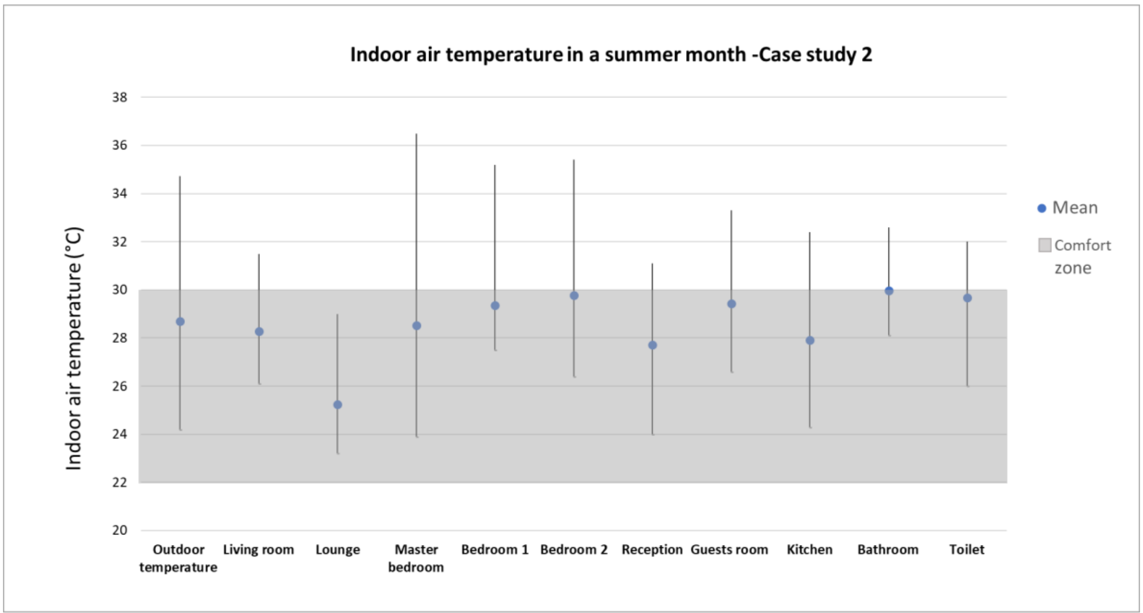


Figure 5. 9 The maximum, mean, and minimum indoor temperature values of different spaces in summer month- Case Study 2

5.3.1.2 During a Winter Month

Figure 5.10 illustrates that the mean air temperatures of all bedrooms during the winter where electrical heaters are used remain within the comfort bands. On the other hand, the mean air temperatures of the other spaces including the living room, reception, and lounge are uncomfortable and fall below the lower band of the comfort zone. The reception and the lounge experience a drop in the mean indoor temperature by 2°C and 3°C, respectively below the lower band of comfort zone. This means that comfort is only obtained when electrical heaters are used.

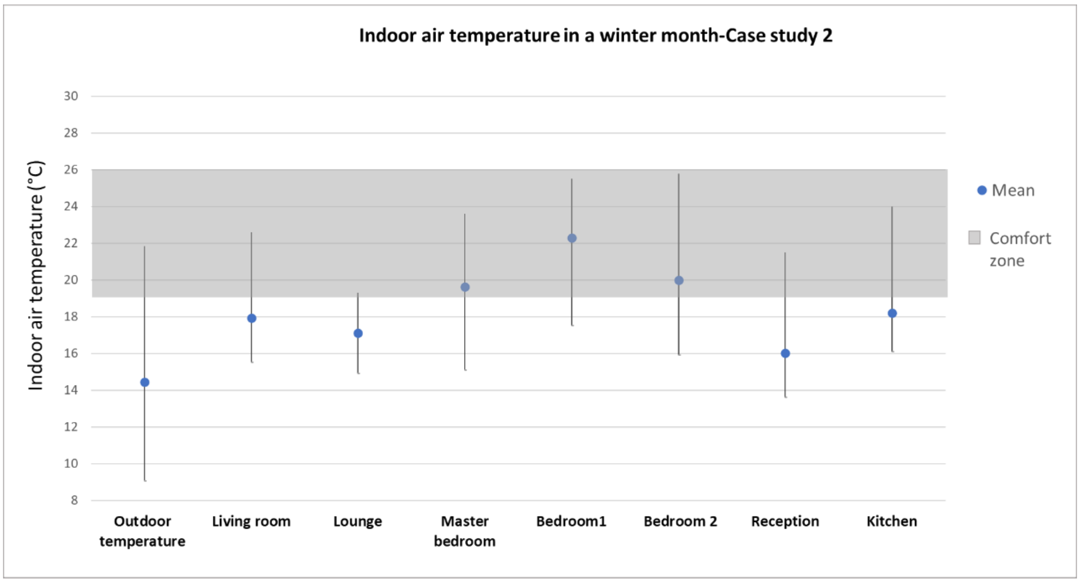


Figure 5. 10 The maximum, mean, and minimum indoor temperature values of different spaces in a winter month- Case Study 2

5.3.1.3 During a Transition Month

In a spring month when no heating and cooling devices are needed, the mean indoor temperatures of all indoor spaces as illustrated in Figure 5.11 remain within the comfort bands.

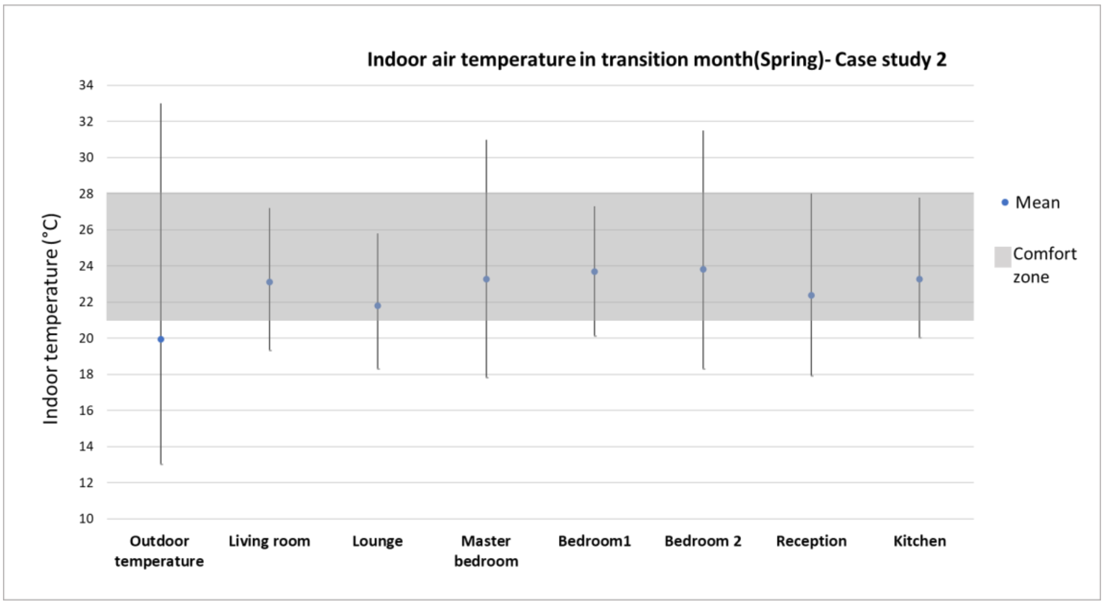


Figure 5. 11 The maximum, mean, and minimum indoor temperature values of different spaces in a transition month- Case Study 2

5.3.1.4 Indoor Temperature Performance When Air Conditioning is On and Off

To assess the indoor temperature performance of the building without the air conditioning, two days from a summer month are selected. One when the electricity is cut off during the daytime and the other day when the air conditioning is running, and both days show similar outdoor temperature ranges. On the 1st of August 2022, there was a power cut from 00:00 to 15:30. The indoor temperature of all spaces is selected and compared with those of comparable hours between 00:00 am and 15:30 on the 30th of July 2022 when the power was on.

It can be observed in Figure 5.12 that when the air conditioning is off, the mean indoor temperatures of all indoor spaces are uncomfortable and fall at or just above the upper band of the comfort zone. On the other hand, when the air conditioning is on, the mean air temperatures of all indoor spaces fall inside the comfort zone. In the spaces where air conditioning units are located, the temperature drops by 1.5°C to 4°C. In other rooms such as bedroom 1 and bedroom 2, the mean air temperatures drop by only 1°C to fall within the comfort zone due to the effect of the air conditioning units that are located in the nearby spaces.

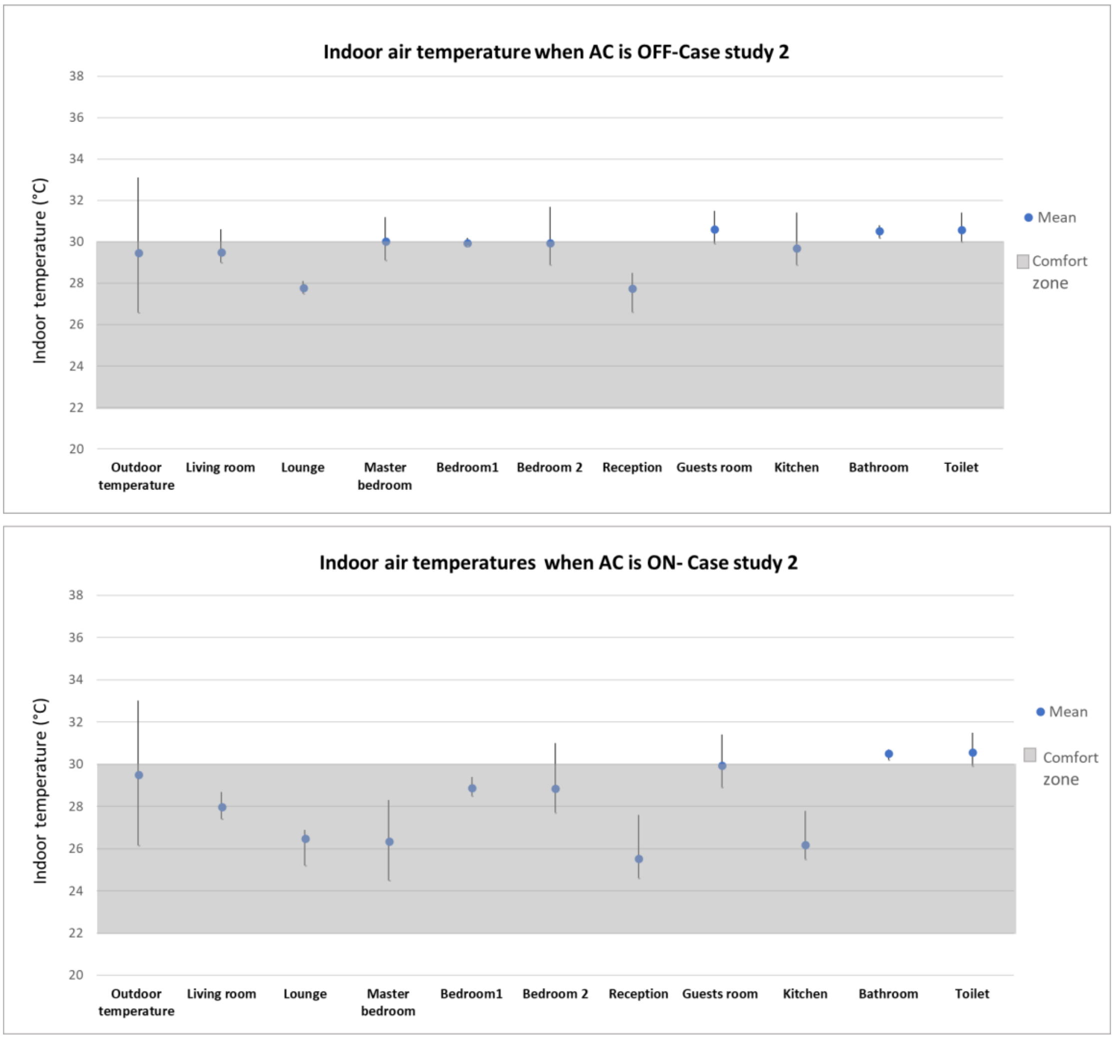


Figure 5. 12 The maximum, mean, and minimum indoor temperature values when air conditioner is ON and OFF

5.3.2 Energy Consumption

The monthly energy consumption of case study 2 in Figure 5.13 shows that the building consumed the most energy in January and August, followed by July, September, and June. April and November witnessed the lowest energy use as there was no need to operate the cooling and heating systems during these months. During one summer month between 7th July 2022 and 5th August 2022, the building consumed 1968.65 kWh. Most of the consumed energy (about 1017 kWh) was used on cooling, making up approximately 51.7% of the total energy consumption. Lighting and other appliances together consumed 39.3% of the total consumed energy while the remaining 9% of the consumed energy was used for domestic hot water DHW (Figure 5.15). In one winter, month between 15th January 2023 and 13th February 2023, the building consumed 2340.36 kWh. More than two-thirds of the used energy (1701 kWh) is attributed to heating at about 73% of the total consumed energy. The remainder of the energy used was divided between domestic hot water and lighting and other appliances combined at 11% and 16%, respectively (Figure 5.16). Thus, most of the energy consumed by the building went on heating and cooling. Therefore, reducing cooling and heating loads must be the primary objectives in order to reduce building energy consumption.

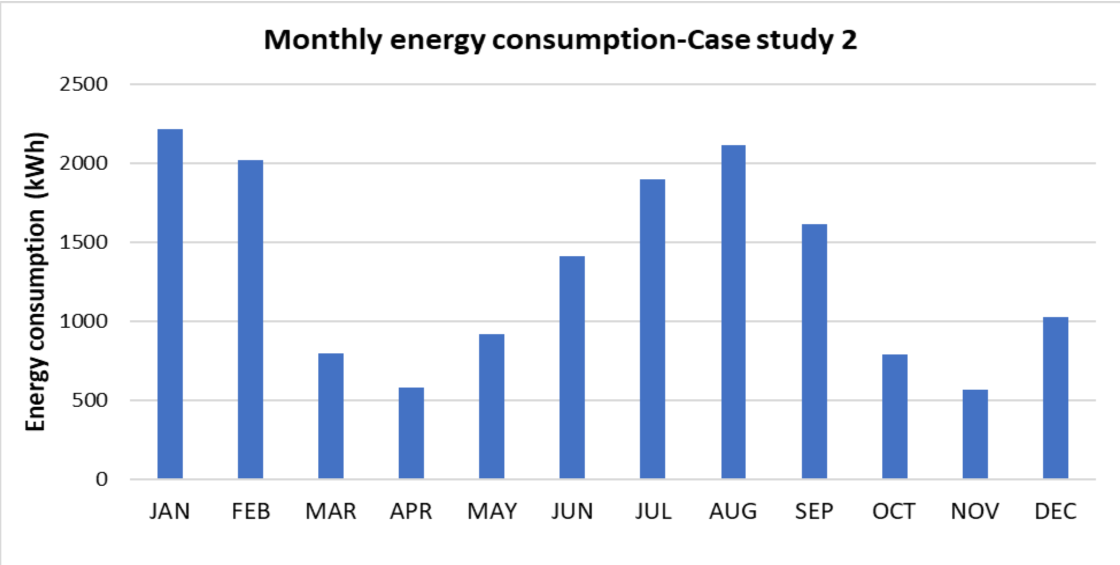


Figure 5. 13 Monthly energy consumption from 7th July 2022 to 6th July 2023

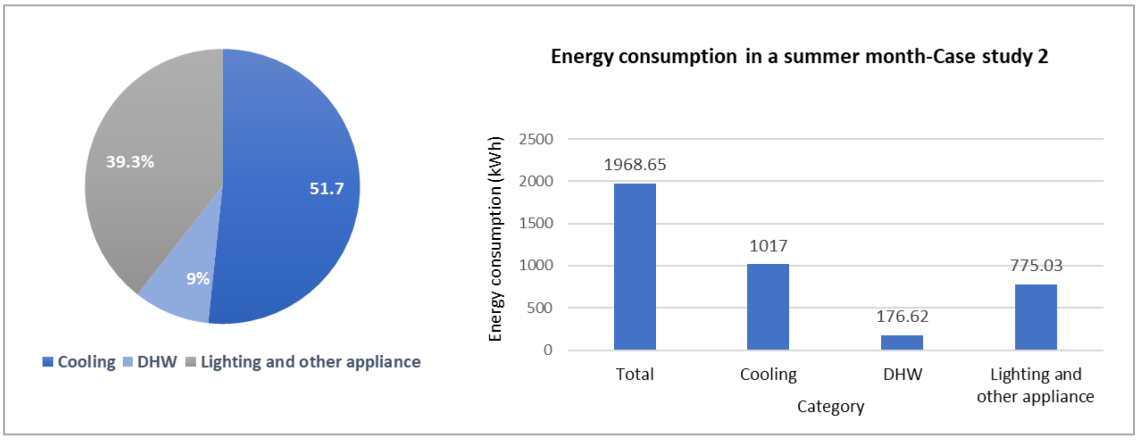


Figure 5. 14 Breakdown of energy consumption of Case Study 2- Summer

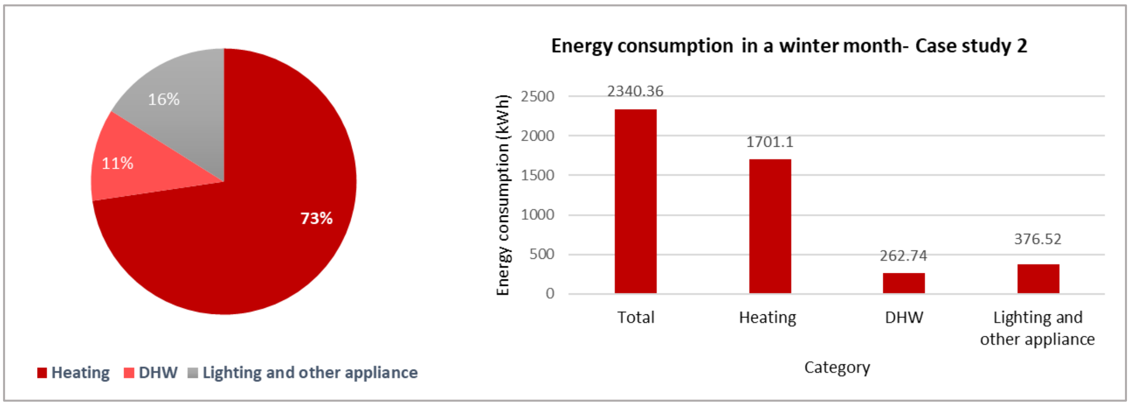


Figure 5. 15 Breakdown of energy consumption of Case Study 2- Winter

5.4 Case Study 3

5.4.1 Indoor Thermal Conditions

5.4.1.1 During a Summer Month

Indoor temperatures of all spaces of the monitored apartment were measured during three seasons. However, to compare the indoor temperature of the monitored apartment that is located on the top floor with the indoor temperature of the lower apartment, two indoor sensors were installed in other apartment. The other apartment is located immediately below the monitored apartment, and its indoor temperature measurement was carried out over a summer month only. Figure 5.16 demonstrates the mean indoor temperatures of indoor spaces of the monitored apartment and two spaces of the lower apartment (L master bedroom and L lounge). Temperature in all spaces of the monitored apartments except for the toilet which is naturally ventilated falls within the comfort zone bands due to the effect of the air conditioning. The lounge and reception where the air conditioning is located, have the lowest mean temperatures. The master bedroom where occupants spend most of the day witnessed the highest mean temperatures. This can be attributed to internal heat gain from occupants and equipment in addition to external heat gain. The L master bedroom and L lounge of the lower apartment have lower mean indoor temperatures compared to the spaces located above it in the monitored apartment taking into account that air conditioning units in both flats are located in the same spaces (lounge and reception). For instance, the temperature in the master bedroom in the monitored apartment is 3°C higher than that of the L master bedroom in the lower flat. A major contributor to this is most likely heat gain from the roof.

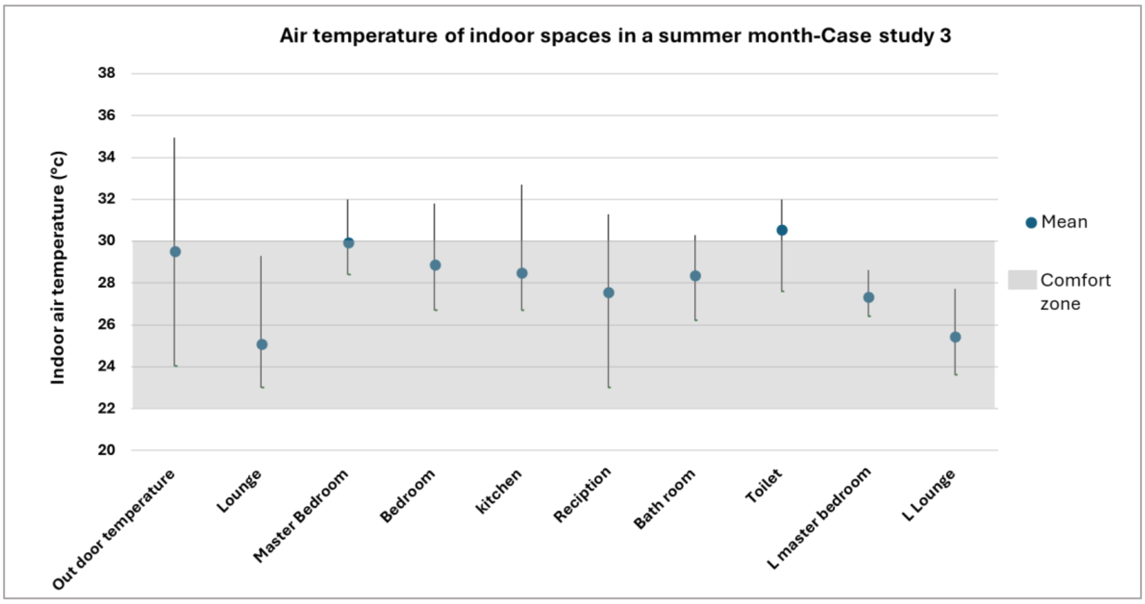


Figure 5. 16 The maximum, mean, and minimum indoor temperature values of different spaces in a summer month- Case Study 3

5.4.1.2 During a Winter Month

In the winter, the mean indoor temperatures of all spaces except for the master bedroom, are uncomfortable and situated below the lower band of comfort zone (Figure 5.17). The master bedroom has a comfortable mean indoor temperature due to the use of electrical heaters.

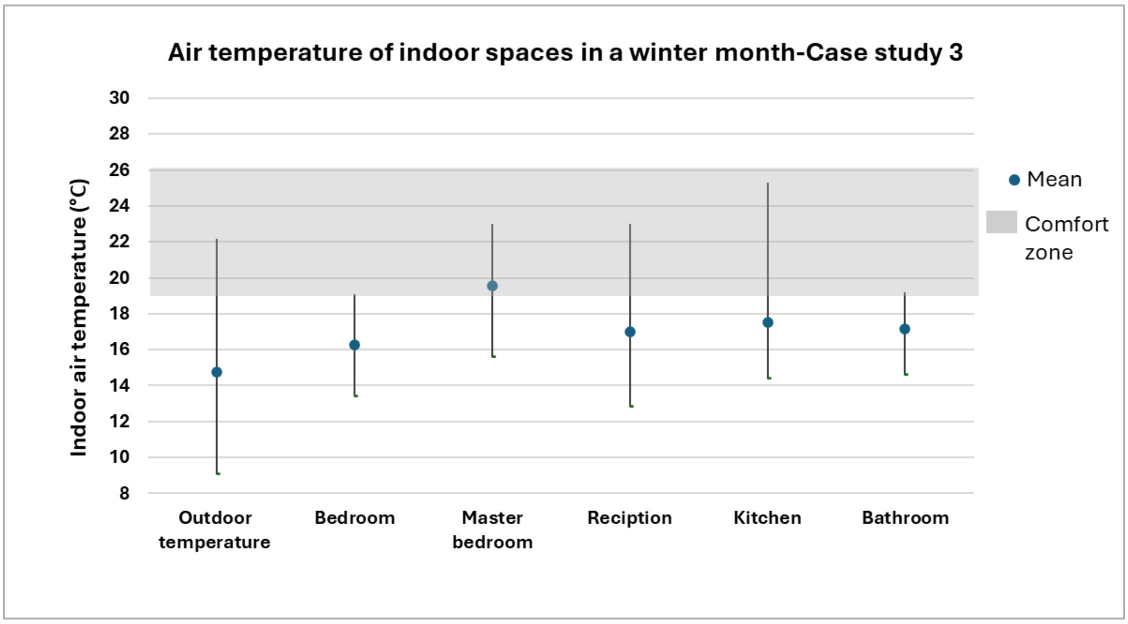


Figure 5. 17 The maximum, mean, and minimum indoor temperature values of different spaces in a winter month- Case Study 3

5.4.1.3 During a Transition Month

In a spring month when no heating and cooling devices are used, the mean indoor temperatures of all indoor spaces as illustrated in the figure 5.18 are situated within the comfort bands.

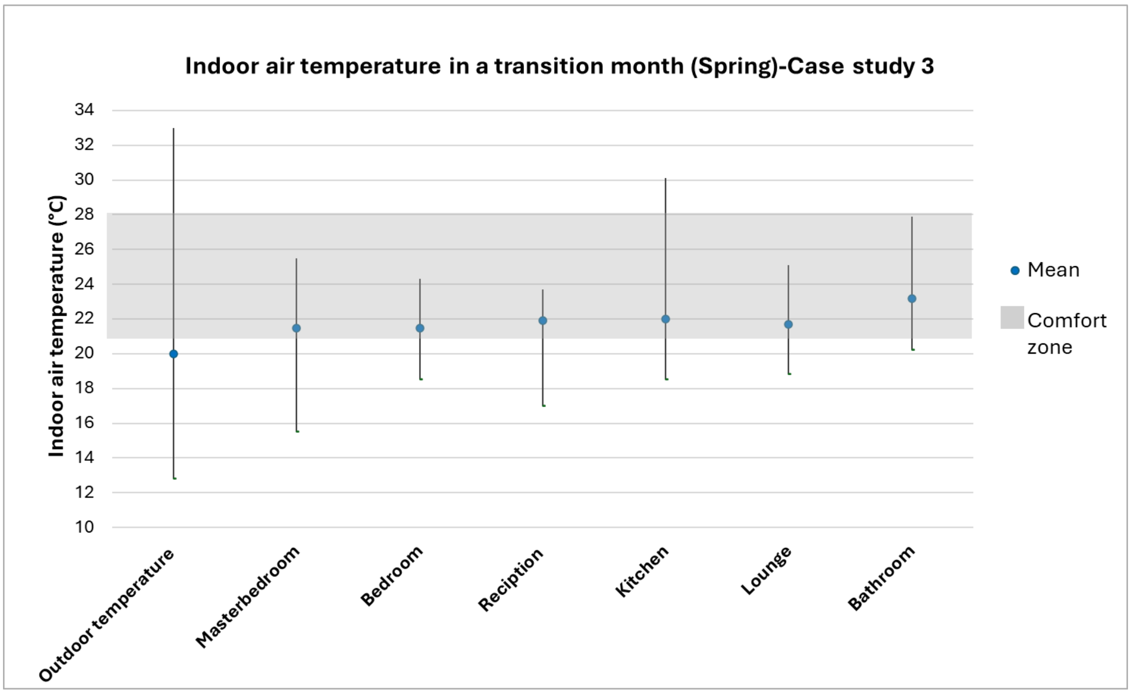
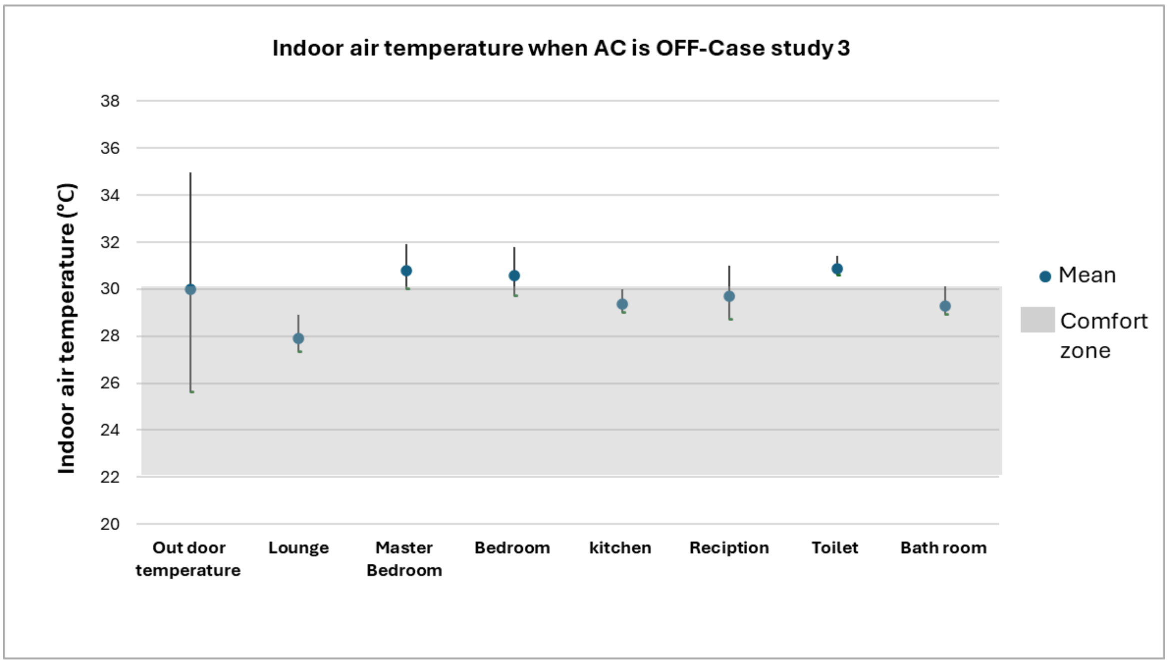


Figure 5. 18 The maximum, mean, and minimum indoor temperature values of different spaces in transition month- Case Study 3

5.4.1.4 Indoor Temperature Performance When Air Conditioner is On and Off

To assess the indoor temperature performance of the building without the air conditioning, two days from one summer month were selected. One when the electricity was cut off during the daytime and the other when the air conditioning was running, and both days showed similar outdoor temperature ranges. On the 12th of August 2022, there was a power cut from 00:00 to 17:00. The indoor temperatures of all spaces were selected and compared with those of comparable hours between 00:00 am and 17:00 on the 7th of August 2022 when the air conditioning was running. Figure 5.19 shows that when the air conditioning is off, the mean indoor temperatures of all indoor spaces are uncomfortable and fall at or just above the upper limit of the comfort zone except for the lounge which is less exposed to the solar radiation than the other spaces. On the other hand, when the air conditioning unit is on, the mean air temperatures of all indoor spaces are decreased by 1.5°C to 2°C to bring indoor temperature to a comfortable level. When the air conditioning is running in the lounge and reception, the temperature drops by 4°C and 6°C, respectively.



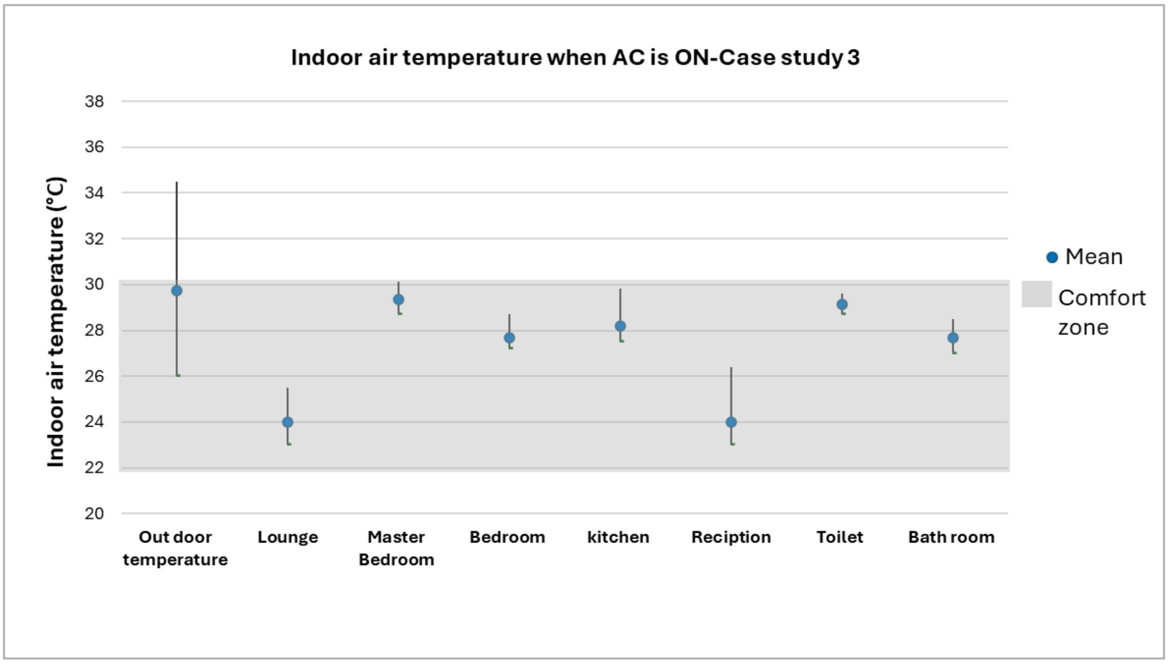


Figure 5. 19 The maximum, mean, and minimum indoor temperature values when air conditioners are ON and OFF

5.4.2 Energy Consumption

The monthly energy consumption of case study 3 in Figure 5.20 shows that the monitored apartment consumed the most energy in the summer months, July, August, and September, followed by December and January in the winter. March, April and October witnessed the lowest energy use as there was no need for cooling and heating during these months. During one summer month, between 7th August 2022 and 6th September 2022, the monitored apartment consumed 1229 kWh. Most of the consumed energy went on cooling at 844.13 kWh making up approximately 68.6% of the total energy consumption. Domestic hot water, lighting, and other appliances consumed the remaining 31.4% of the consumed energy (Figure 5.21). In a winter month, between 15th January 2023 and 13th February 2023, the monitored apartment consumed 873.05 kWh. Most of the consumed energy, approximately 610 kWh, went on heating which constituted more than two-thirds of the used energy (69.9%). The remainder of the energy used was divided between domestic hot water, lighting, and other appliances at 30.1% (Figure 5.22). Consequently, most of the energy consumed went on heating and cooling. Therefore, reducing the load for heating and cooling must be the primary objective to reduce the building's energy consumption.

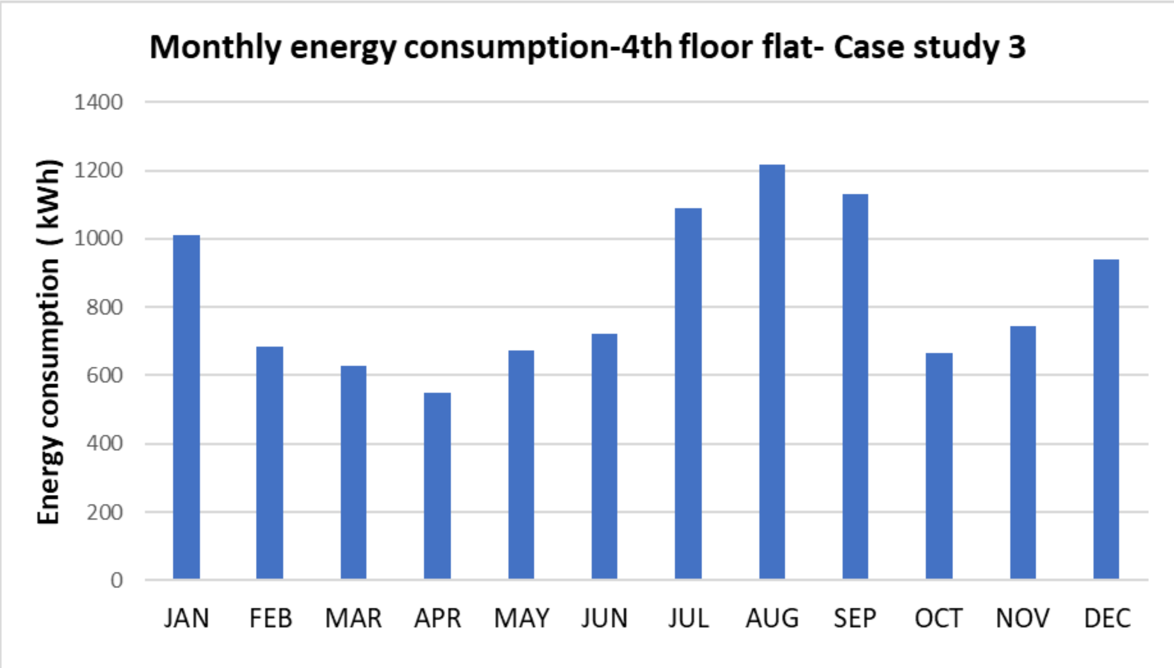


Figure 5. 20 Monthly energy consumption from 7th August 2022 to 6th August 2023

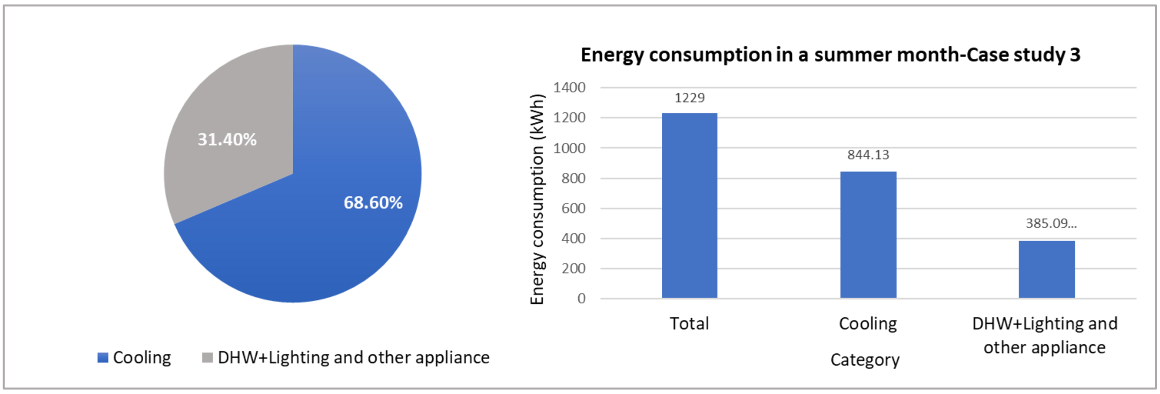


Figure 5. 21 Breakdown of energy consumption of Case Study 3- Summer

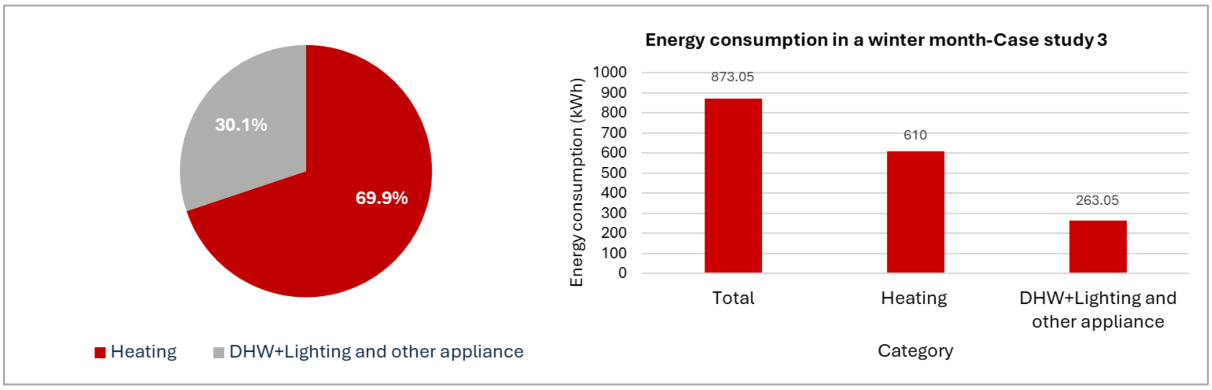


Figure 5. 22 Breakdown of energy consumption of Case Study 3- Winter

5.5 Discussion of Building Monitoring Study Results

Case Study 1

For the terraced house (Case Study 1), the breakdown of energy consumption in summer and winter months revealed that the building consumes the most energy on cooling in summer and heating in winter. As around 70% of the building's external walls are adjacent to the neighbouring houses which are assumed to have similar average indoor temperatures as the case study building, heat gain, and loss through the walls are expected to be lower than that through the roof which is more exposed to the direct solar radiation and has higher U-value than the walls. This finding can also be addressed by the temperature difference between the ground floor and the first floor where the ground floor spaces have lower temperatures than the first-floor spaces. Investigating indoor temperature on the first floor when the air conditioning is on and off reveals that although there is air conditioning on the first floor, it fails to bring the indoor temperature to a comfortable level. This indicates that due to the absence of insulation material, the heat gain through the roof and walls is greater than what the air conditioning system can remove.

In the winter, the first floor consumed about ten times more energy than the ground floor, which can also be attributed to heat loss through the roof. Heat gain and loss through the openings are assumed to be less than through the roof and walls due to the low window to wall ratio. As a result, upgrading the building's roof and walls could have the highest impact on energy use reduction, and securing comfortable indoor temperatures. This assumption is investigated later in the simulation study.

Case Study 2

The breakdown of energy consumption in the summer and winter months of the detached house (Case Study 2) demonstrates that the building consumes the most energy for cooling and heating. The mean indoor air temperatures in all indoor spaces are comfortable due to the effect of the air conditioning, and those where air conditioning units are installed have the lowest indoor temperatures. Similarly in the winter, only indoor spaces with electrical heaters are comfortable. The analysis of indoor temperatures when the air conditioning unit is off and on revealed that when the air conditioning unit is off all spaces witness an increase in the mean indoor temperatures to an uncomfortable level. This means that comfort level in indoor spaces cannot be achieved unless air conditioning is used in the summer and electrical heaters are used in winter. Similarly to Case Study 1, heat gain and loss through the roof and walls are assumed to be the main contributors to the increase in the cooling and heating energy need. This is attributed to the high U-values of the roof and walls. Solar gain through the opening is assumed to be less than through the roof and walls due to the low window to wall ratio. This assumption is investigated later in the simulation study.

Case Study 3

For the apartment building (Case Study 3), the breakdown of energy consumption in the summer and winter months of only one apartment located on the top floor (4th floor) reveals that the apartment as terraced house and detached house consumes the most energy for cooling in summer and heating in winter. The mean indoor air temperatures in all indoor spaces are comfortable due to the effect of the air conditioning, and those where the air conditioning units are installed have the lowest indoor temperatures. Similarly in the winter, only indoor spaces with electrical heaters are comfortable. The analysis of indoor temperatures when the air conditioning unit is off and on reveals that when the conditioning unit is off all spaces witness an increase in the mean indoor temperature. This means that comfort level in indoor spaces cannot be achieved unless air conditioning is used in summer and electrical heaters are used in winter. Similarly to Case Study 1, and Case Study 2, heat gain and loss through the roof and walls are assumed to be the main contributors to the increase in the cooling and heating energy need. This is attributed to the high U-values of the roof and walls. However, the heat gain and loss through the external walls could be higher than the roof due to their large surface area compared to the roof. Solar gain through the opening is assumed to be less than through the roof and walls due to the low window to wall ratio. These assumptions are investigated later in the simulation study.

5.6 Chapter Summary

This chapter aimed to provide a general understanding of the energy performance and thermal conditions of the case study buildings by analysing the collected data on energy consumption, and outdoor and indoor temperature for the summer, winter, and transitional seasons. The monthly energy consumption of all the case studies was measured and the data analysis showed that the buildings consume the most energy in August and January. However, the months of June, July, and September also witnessed high energy consumption in all the case study buildings. March, April October, and November showed the lowest energy use as there was no need for cooling or heating systems during these months. The evaluation of thermal performance was investigated based on ASHRAE 55- 2017 criteria. The initial analysis of the collected data showed that the mean indoor temperature in summer is maintained within the comfort zone only when air conditioning units are used, and comfortable in winter only when electrical heaters are used. This was demonstrated by contrasting the mean indoor temperature when the air conditioning is on and off. In addition, the three case study buildings consume most of the energy for cooling and heating that could be plausibly attributed to the heat gain and loss through the buildings' walls and roof due to the absence of insulation. Glazing seems to have less influence on cooling and heating energy need due to the low window to wall ratio in the three case study buildings. Chapter 7 will describe the numerical simulation result to identify the drivers of cooling and heating loads and compare the results with those of the monitoring study. The following chapter conducts building calibration simulation to improves the accuracy and reliability of the case study building models.

Chapter 6: Building Calibration Simulation - Results and Discussion

6.1 Introduction

A key objective of this study is to examine the impact of different energy-saving measures on the energy and thermal performance of three case study residential buildings. To ensure that the building models closely represent the actual buildings, and to obtain a reliable simulation outcomes, the case study models were calibrated using real-time monitoring data in DesignBuilder. The research methodology discussion in Chapter 3 presented in detail the procedure adopted for the generation of simulation models within the context of the calibration process. This chapter presents the results and analysis for the calibration simulation study. Measured energy consumption and indoor air temperature were compared by applying ASHRAE Guideline 14-2002 calibration criteria with the simulated data to assure the accuracy and reliability of the building models (ASHRAE14 2002). The entire calibration process comprises four approaches: monthly energy consumption calibration; hourly energy consumption calibration; monthly zone temperature calibration; and hourly zone temperature calibration.

6.2 Calibration Results for Case Study Building 1

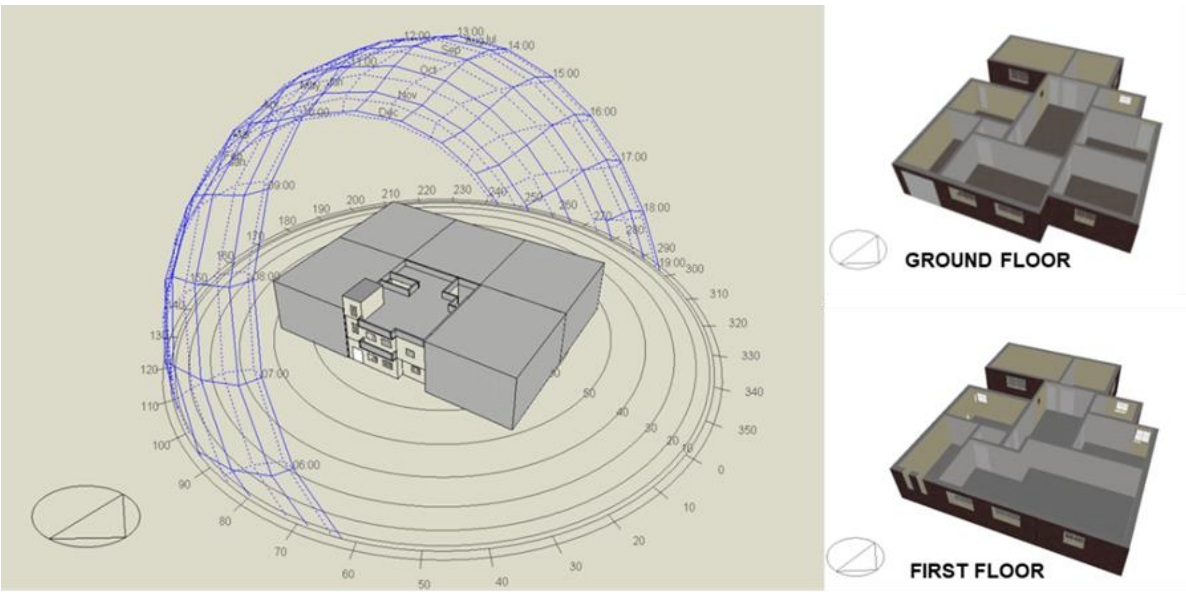


Figure 6. 1 Case Study Building 1 modelling in DesignBuilder.

6.2.1 Setting Up the Sensitivity Analysis

Sensitivity analysis was used to determine the most and least influential parameters on the cooling and heating load of the Case Study 1 model. Cooling load and heating load were selected as objective functions for the sensitivity analysis as they were the key contributors to the energy consumption of case study building 1. A primary sensitivity test was conducted on 14 parameters to assist the calibration stage by identifying the hierarchical order of the sensitive parameters. Once these parameters had been determined, the values of the least influential parameters were removed from further consideration, and those of the most influential ones were tuned manually until an acceptable discrepancy between measured and simulated data was achieved. In this study, the method applied in the sensitivity analysis was regression, which is an existing feature of DesignBuilder. The indicating factor was the standardised regression coefficient (SRC), and the number of random simulations was chosen as 100 times the number of design parameters. Table 6.1 shows the parameters that were chosen for sensitivity analysis for Case Study 1.

Table 6. 1 Selected parameters for sensitivity analysis- case study 1

	Parameters	**Distribution category**	**Distribution curve**	**Distribution summary**	**Target objects**
Flat roof construction	Flat roof construction	1-Discrete	20-Uniform (Discrete)	Prob:0.200; Options:5	Building
FF external wall construction	External wall construction	1-Discrete	20-Uniform (Discrete)	Prob:0.167; Options:6	1 target selected
GF external wall construction	External wall construction	1-Discrete	20-Uniform (Discrete)	Prob:0.167; Options:6	1 target selected
Ground floor construction	Ground floor construction	1-Discrete	20-Uniform (Discrete)	Prob:0.167; Options:6	Building
Glazing type	Glazing type	1-Discrete	20-Uniform (Discrete)	Prob:0.200; Options:5	Building
Local shading type	Local shading type	1-Discrete	20-Uniform (Discrete)	Prob:0.250; Options:4	Building
Window to wall ratio %	Window to wall ratio %	2-Continuous	Normal	Mean:40	Building
Equipment power density (w/m²)	Equipment power density (w/m²)	2-Continuous	Normal	Mean:5	Building
Occupancy (Days/Weeks)	Occupancy (Days/Weeks)	1-Discrete	20-Uniform (Discrete)	Min.Val:0.00; Step size:1.00; Step No:8.00	Building
Infiltration rate (ac/h at 50 Pa))	Infiltration rate (ac/h at 50 Pa)	2-Continuous	Normal	Mean:6	Building
Cooling system Seasonal COP	Cooling system Seasonal COP	2-Continuous	Normal	Mean:2.5	Building
Heating system Seasonal COP	Heating system Seasonal COP	2-Continuous	Normal	Mean:2.5	Building

Cooling set-point temperature (C°)	Cooling set-point temperature (C°)	2-Continuous	Normal	Mean:25	Building
Heating set-point temperature (C°)	Cooling set-point temperature (C°)	2-Continuous	Normal	Mean:20	Building

6.2.1.1 Sensitivity Analysis Results

When the energy consumption of measured and simulated end-use for the summer and winter months were compared, there was a discrepancy in cooling and heating energy, while the other categories (DHW, lighting, and other appliances) showed good agreement. Simulated indoor temperature also showed a good agreement with the monitored indoor zone temperature.

Sensitivity analysis was carried out to determine the most sensitive design parameters for cooling and heating loads that can be adjusted to reduce the discrepancy between measured and simulated cooling and heating energy use. According to the sensitivity analysis results of case study 1 (Figure 6.2), the design parameters are the most influential parameters on cooling load. The roof and the first-floor wall constructions have the greatest influence on the cooling load. Cooling load is moderately influenced by ground wall construction, ground floor construction, local shading, and glazing type. The occupancy schedule, window-to wall ratio (WWR), cooling system coefficient of performance (COP), cooling setpoint temperature, equipment power density, and infiltration rate do not have any notable impact on cooling load and can therefore be ignored in the parameter adjustment step. The heating load sensitivity analysis results illustrate that roof, and the first-floor walls have the greatest influence on heating load. The ground floor wall construction has a moderate influence, while local shading and glazing type have a very limited influence on heating load (Figure 6.3). As a result, adjusting these design parameters helps reduce the discrepancy between the actual and simulated model results. However, since the U-value specifications of the ground floor walls and first floor walls were set based on actual measurements, both were exempt from the parameter adjustment step. Therefore, only the design parameters specifications for roof and floor construction were tuned manually until an acceptable discrepancy between the monitored and simulated data was achieved.

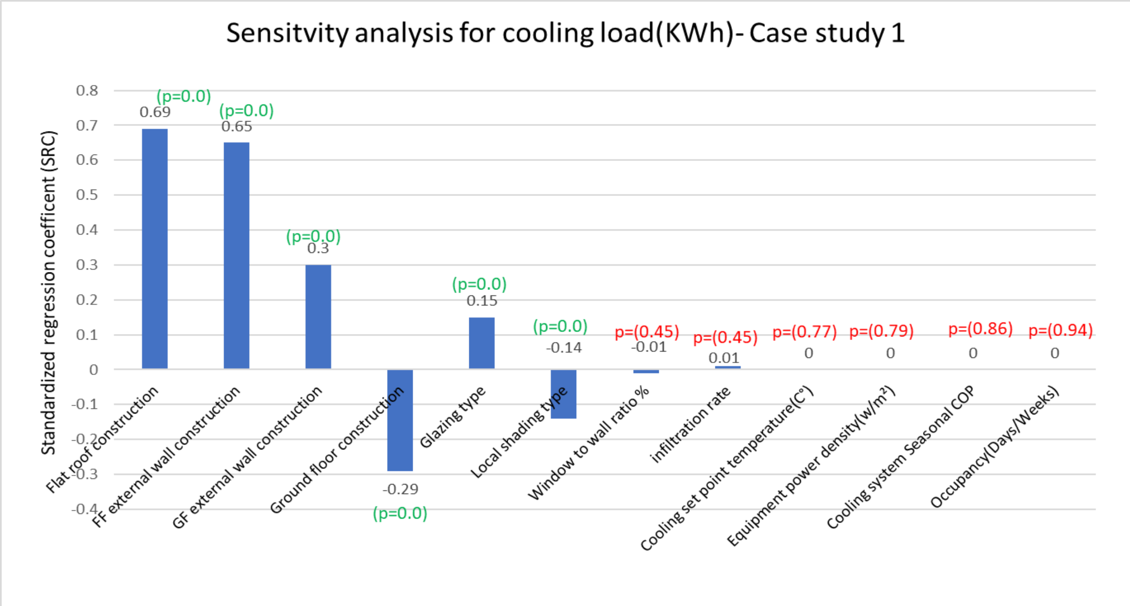


Figure 6. 2 Cooling load sensitivity analysis results - Case Study 1

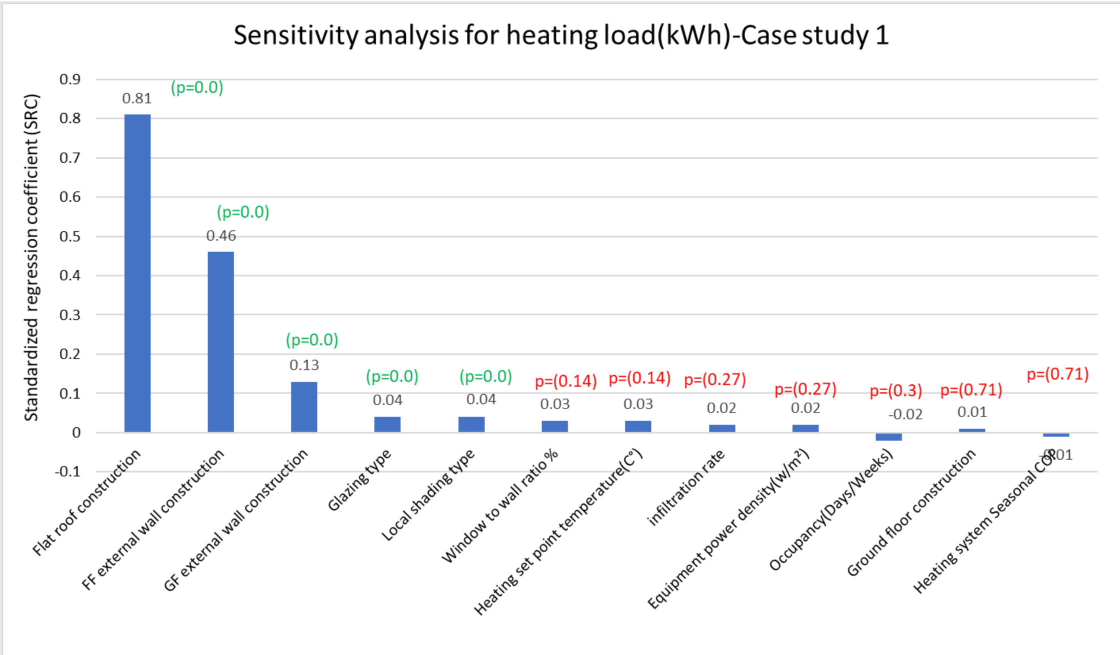


Figure 6. 3 Heating load sensitivity analysis results - Case Study 1

6.2.2 Monthly Energy Consumption Calibration

Figure 6.4 compares the monthly simulation results and monitored energy consumption data and provides the key statistical error values. According to ASHRAE Guideline 14-2002, the monthly energy use profile was estimated with an acceptable degree of accuracy: i.e., CV (RMSE) < 15% and NMBE < ±5%.

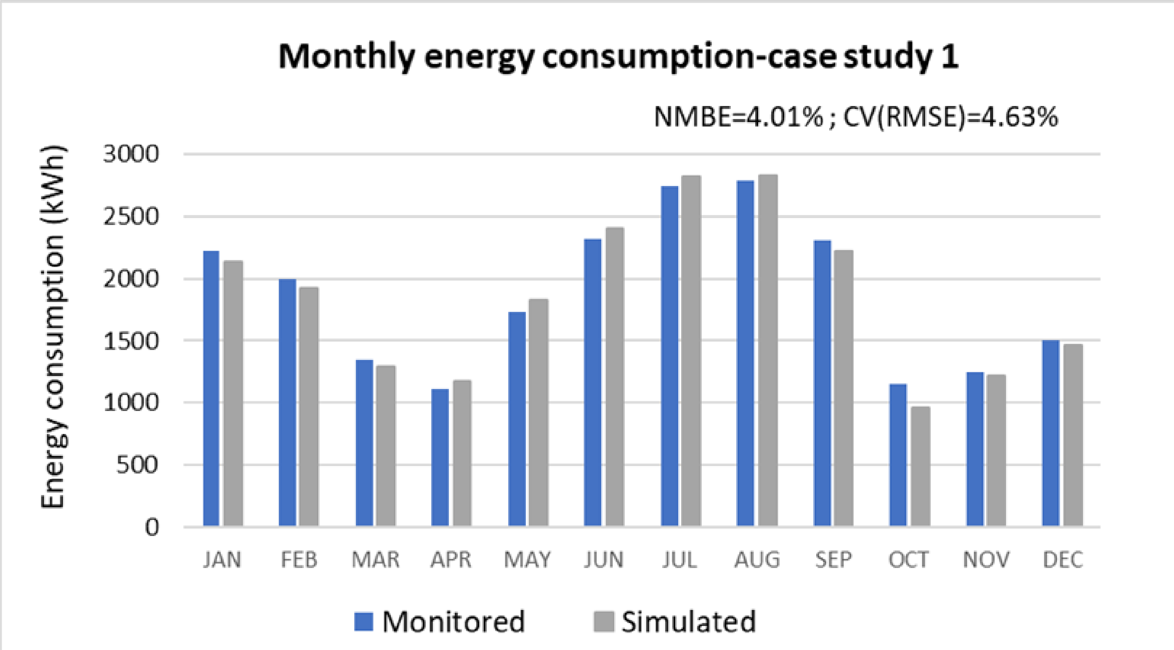


Figure 6. 4 Monthly energy consumption calibration results for Case Study 1

6.2.3 Hourly Energy Consumption Calibration

Initial checks confirmed that the measured and simulated energy consumption were correlated and in agreement to some extent. This can be seen when examining the overall trends in measured and simulated energy consumption between 19th June and 22nd June 2022 (Figure 6.5). However, an evaluation of the hourly NMBE and CV(RMSE) showed a discrepancy between monitored and simulated data. To investigate the reasons for the fluctuation in the actual energy consumption trend which caused the discrepancy, the actual energy use data for the AC unit was compared to the actual temperature trend in the lounge, where the AC is situated. It was found that the times when AC energy use was recorded as zero were the times when the indoor temperature reached the AC set point of 24 °C (Figure 6.6).

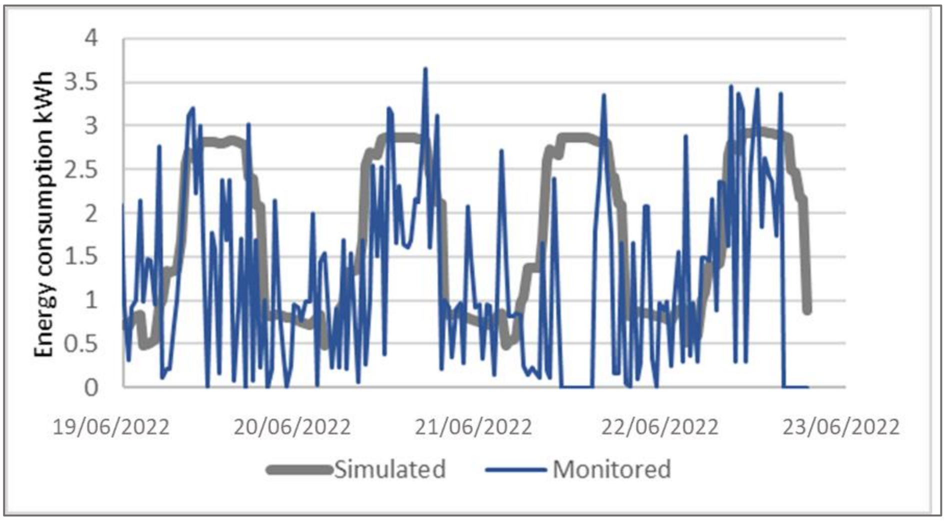


Figure 6. 5 General trend in simulated versus monitored energy use data between 19th and 22nd June 2022

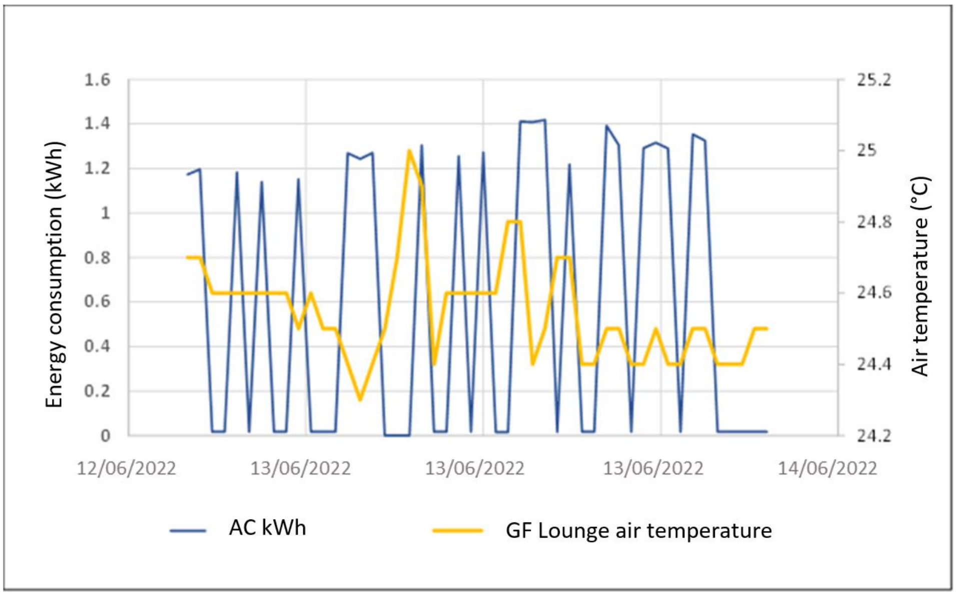


Figure 6. 6 Air temperature of the ground floor lounge against AC energy use.

Due to the variability of the measured energy use, it was challenging to calibrate hourly energy consumption. For this reason, the running average of the measured data was used to help smooth its fluctuating pattern and then compared to the running average of the simulation outputs. When comparing the running average of measured energy consumption data against the running average of simulated data in Figures 6.7- 6.8, it can be noticed that the general patterns of both are correlated very closely, which facilitates model calibration based on energy consumption using ASHRAE 14 calibration criteria.

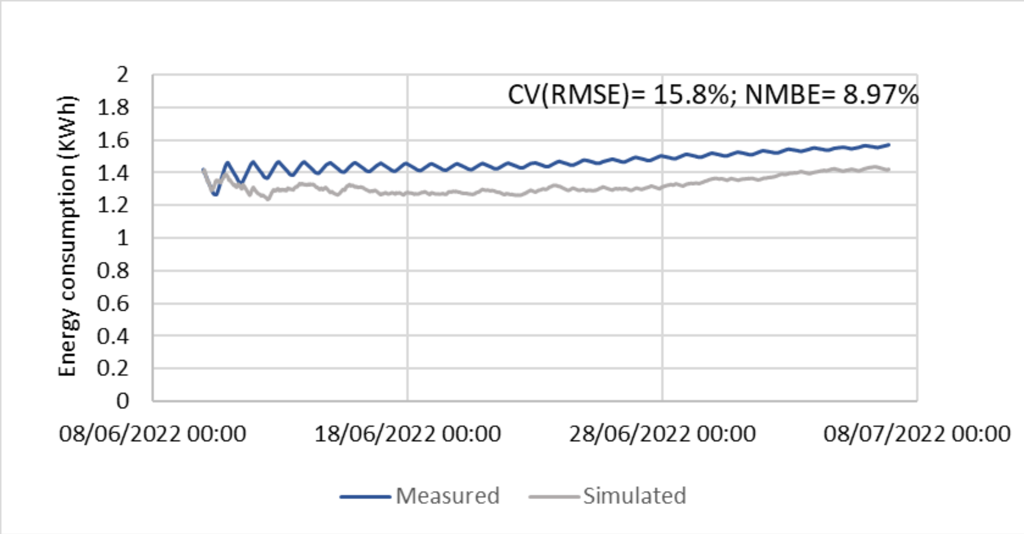


Figure 6. 7 Running average of measured and simulated building energy consumption in one summer month, between 8th of June 2022 and 6th of July 2022.

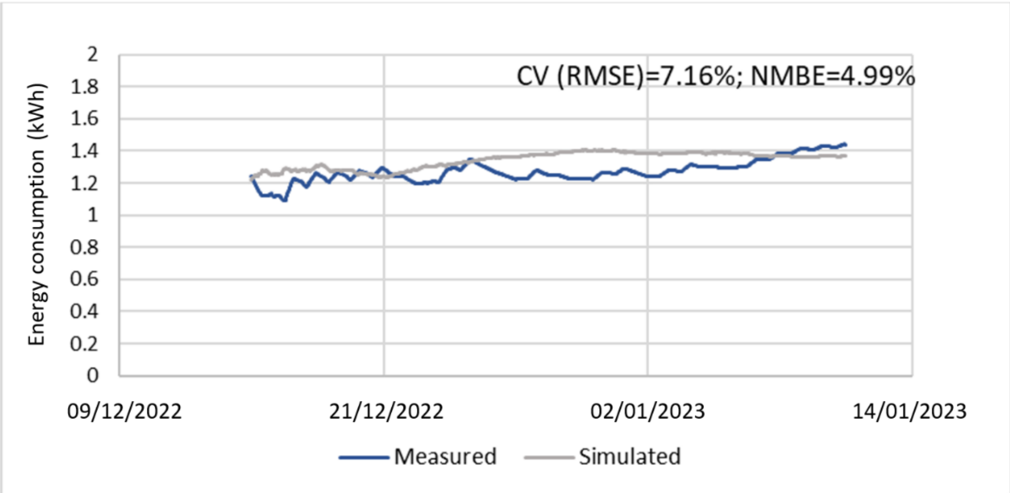


Figure 6. 8 Running average of measured and simulated building energy consumption in one winter month, between 12th December 2022 and 10th January 2023.

6.2.4 Monthly Zone Temperature Calibration

Zone temperature calibration is also adopted in this research to ensure that the calibrated model properly reflects the actual building's performance. Figures 6.9 - 6.10 show that the simulated average indoor temperature of randomly selected spaces on the ground floor and first floor closely follow the measured average indoor temperature. Moreover, an acceptable CV(RMSE), and NMBE are also achieved for all selected zones. Thus, the model is considered calibrated based on monthly zone temperature.

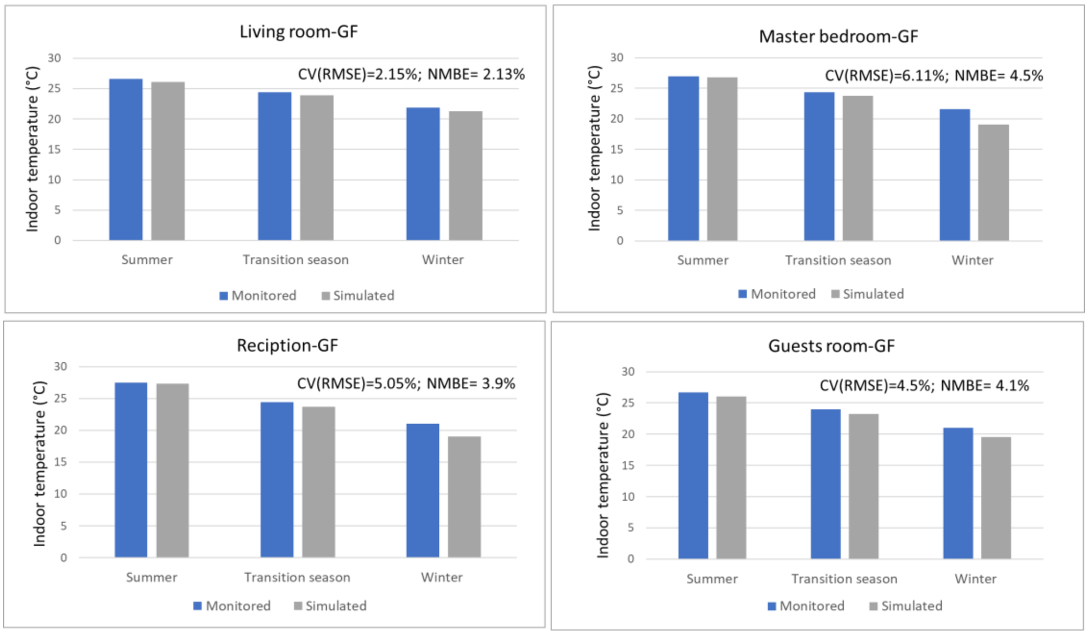


Figure 6. 9 Monthly zone temperature calibration of ground floor spaces- Case Study 1.

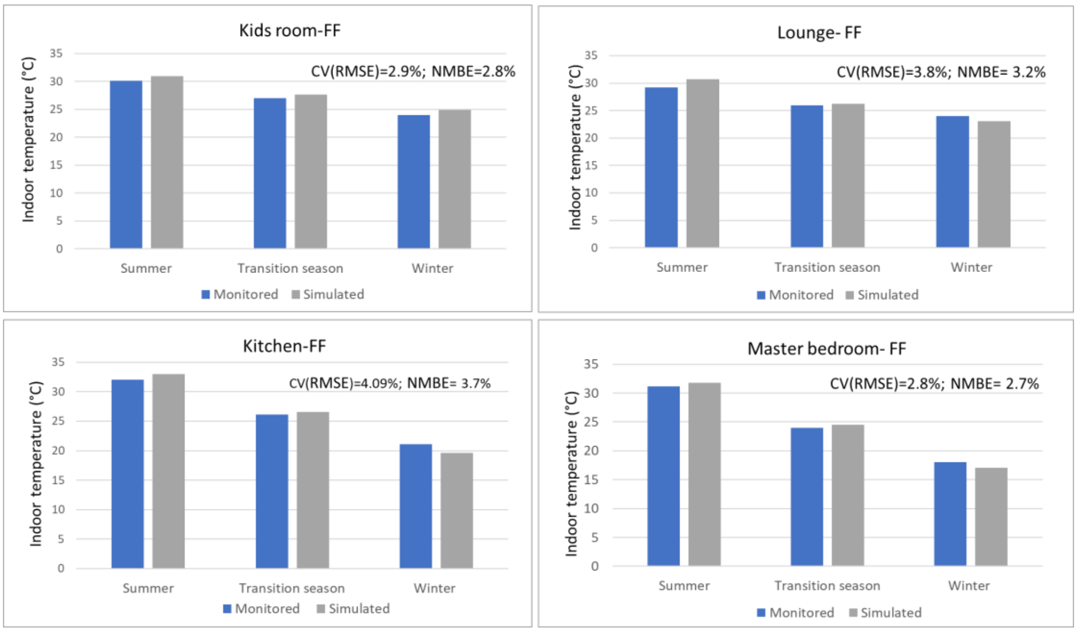


Figure 6. 10 Monthly zone temperature calibration of first floor spaces- Case Study 1.

6.2.5 Hourly Zone Temperature Calibration

To ensure that the calibrated model reasonably reflected the actual building's performance, hourly zone temperature calibration was carried out for the summer month. The monitored indoor temperature data for ground floor and first floor spaces were also compared to the simulated data. The simulated temperatures closely follow the measured air temperature, as shown in Figures 6.11-6.12. Moreover, an acceptable hourly NMBE and CV(RMSE) are also achieved for all selected zones.

As a result, the calibrated model properly reflects the actual building's performance and is validated for simulation study.

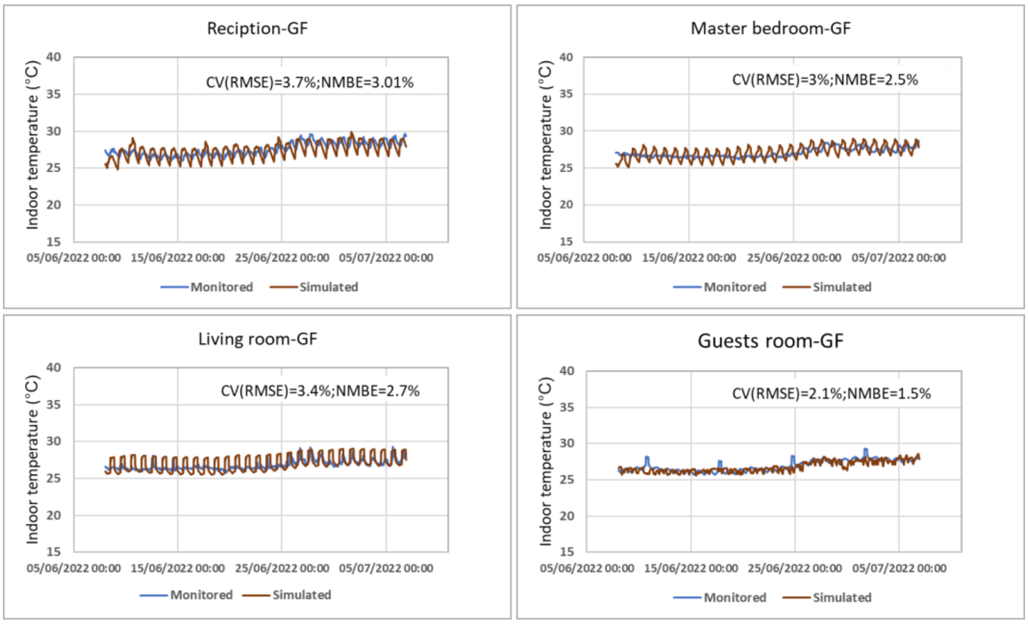


Figure 6. 11 Hourly zone temperature calibration of ground floor spaces - Case Study 1

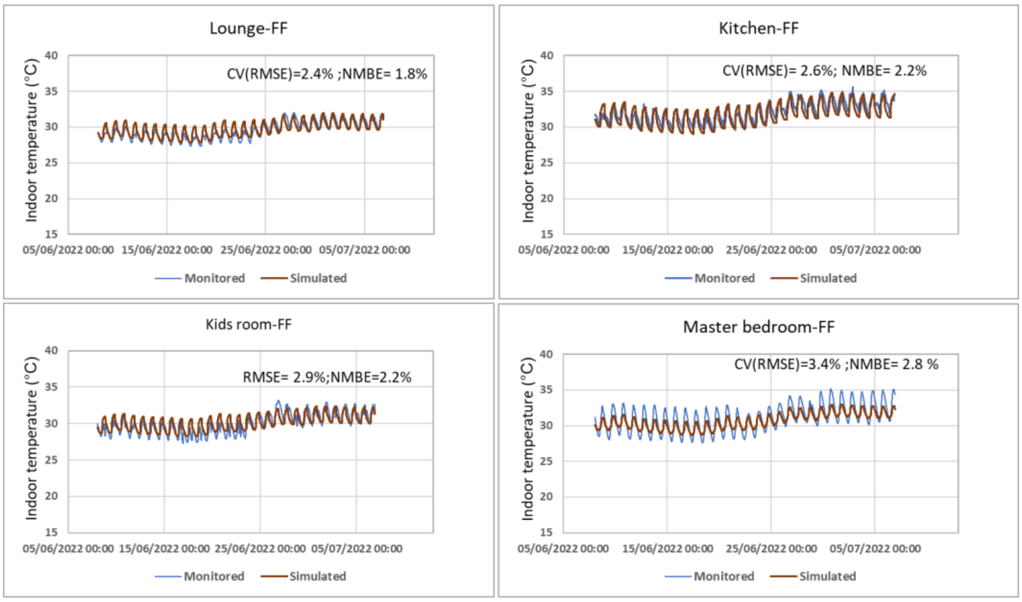
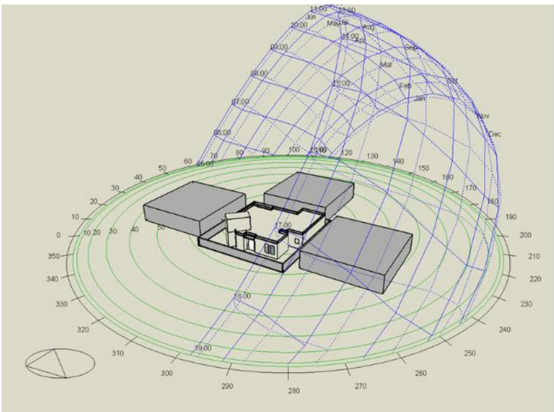


Figure 6. 12 Hourly zone temperature calibration of first floor spaces - Case Study 1

6.3 Calibration Results for Case Study Building 2



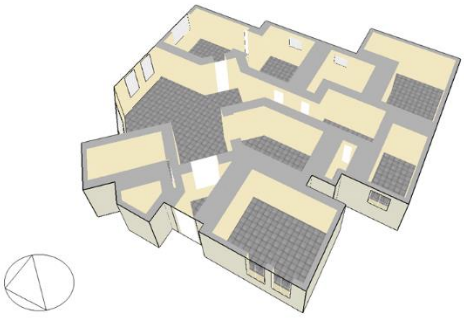


Figure 6. 13 Case Study building 2 modelling in DesignBuilder.

6.3.1 Setting Up the Sensitivity Analysis

Cooling load and heating load were set as objective functions for the sensitivity analysis as they are determined as the key contributors to the energy consumption of Case Study building 2. The sensitivity test was conducted on 13 parameters to assist the calibration stage by identifying the hierarchical order of the sensitive parameters. Once these parameters were determined, the values of the least influential parameters were removed from further consideration, and the most influential ones were tuned manually until an acceptable discrepancy between measured and simulated data was achieved. The number of random simulations was chosen as 100 times the number of design parameters. Table 6.2 shows the parameters that were chosen for sensitivity analysis for Case Study 2.

Table 6. 2 Selected parameters for sensitivity analysis - case study 2.

	Parameters	Distribution category	Distribution curve	Distribution summary	Target objects
Flat roof construction	Flat roof construction	1-Discrete	20-Uniform (Discrete)	Prob: 0.200; Options: 5	Building
External wall construction	External wall construction	1-Discrete	20-Uniform (Discrete)	Prob: 0.167; Options: 6	Building
Ground floor construction	Ground floor construction	1-Discrete	20-Uniform (Discrete)	Prob: 0.167; Options: 6	Building
Glazing type	Glazing type	1-Discrete	20-Uniform (Discrete)	Prob: 0.200; Options: 5	Building
Local shading type	Local shading type	1-Discrete	20-Uniform (Discrete)	Prob: 0.250; Options: 4	Building

Window to wall ratio %	Window to wall ratio %	2-Continuous	Normal	Mean: 40	Building
Equipment power density (w/m²)	Equipment power density (w/m²)	2-Continuous	Normal	Mean: 5	Building
Occupancy (Days/Weeks)	Occupancy (Days/Weeks)	1-Discrete	20-Uniform (Discrete)	Min.Val: 0.00; Step size: 1.00; Step No: 8.00	Building
Cooling system Seasonal COP	Cooling system Seasonal COP	2-Continuous	Normal	Mean: 2.5	Building
Heating system Seasonal COP	Heating system Seasonal COP	2-Continuous	Normal	Mean: 2.5	Building
Cooling set-point temperature (C°)	Cooling set-point temperature (C°)	2-Continuous	Normal	Mean: 25	Building
Heating set-point temperature (C°)	Cooling set-point temperature (C°)	2-Continuous	Normal	Mean: 20	Building
Infiltration rate (ac/h at 50 Pa))	Infiltration rate (ac/h at 50 Pa)	2-Continuous	Normal	Mean: 6	Building

6.3.1.1 Sensitivity Analysis Result

According to the sensitivity analysis result of Case Study 2, the standardized regression coefficient of the cooling load shows that the most influential design parameters is ground floor construction (Figure 6.14). The figure also shows that the cooling load is also sensitive to external wall construction and flat roof construction. Cooling load is moderately influenced by local shading, cooling setpoint temperature, and infiltration rate. Glazing type, window-to-wall ratio, cooling system coefficient of performance (COP), and equipment power density, do not have any notable impact on cooling load and can therefore be ignored in the parameter adjustment step. The heating load sensitivity analysis results illustrate that the external wall construction, flat roof construction, and ground floor construction have the greatest influence on heating load. Glazing type, heating setpoint temperature, and infiltration rate have a moderate influence, while local shading, glazing type, window-to-wall ratio, heating system COP, and equipment power density, have a very limited influence on heating load (Figure 6.15). Adjusting design parameters that have a high and moderate influence on cooling and heating loads helps reduce the discrepancy between the actual and simulated model results. However, since the U-value specifications of the wall were set based on actual measurements, they were exempt from the parameter adjustment step. Design parameters specifications of the flat roof construction, ground floor construction, cooling set point, and heating set point were tuned manually until an acceptable discrepancy between the monitored and simulated data was achieved.

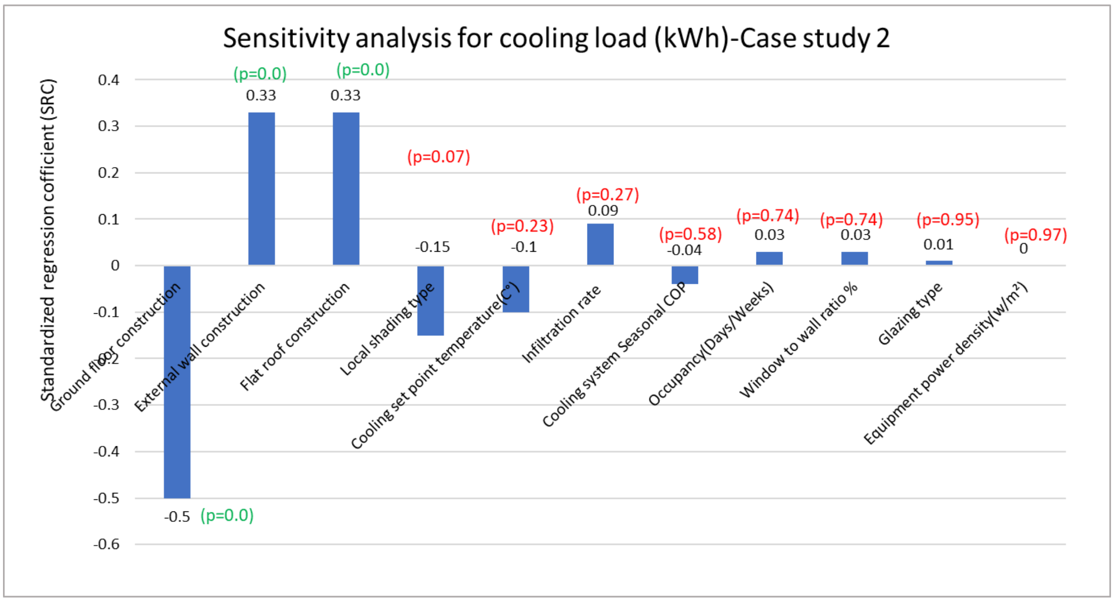


Figure 6. 14 Cooling load sensitivity analysis result - Case Study 2

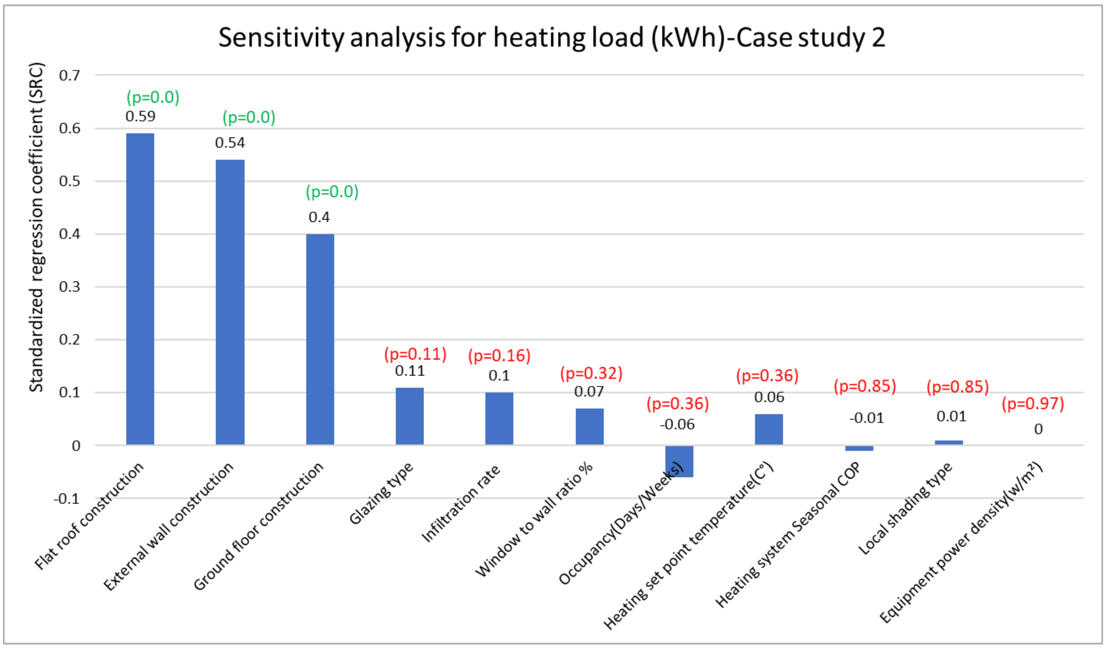


Figure 6. 15 Heating load sensitivity analysis result- Case Study 2

6.3.2 Monthly Energy Consumption Calibration

Figure 6.16 compares the monthly simulation results and the monitored data for energy consumption and provides the key statistical error values. Following ASHRAE Guideline 14-2002, the monthly energy use profile was estimated with an acceptable degree of accuracy: i.e., CV (RMSE) < 15% and NMBE < ±5%.

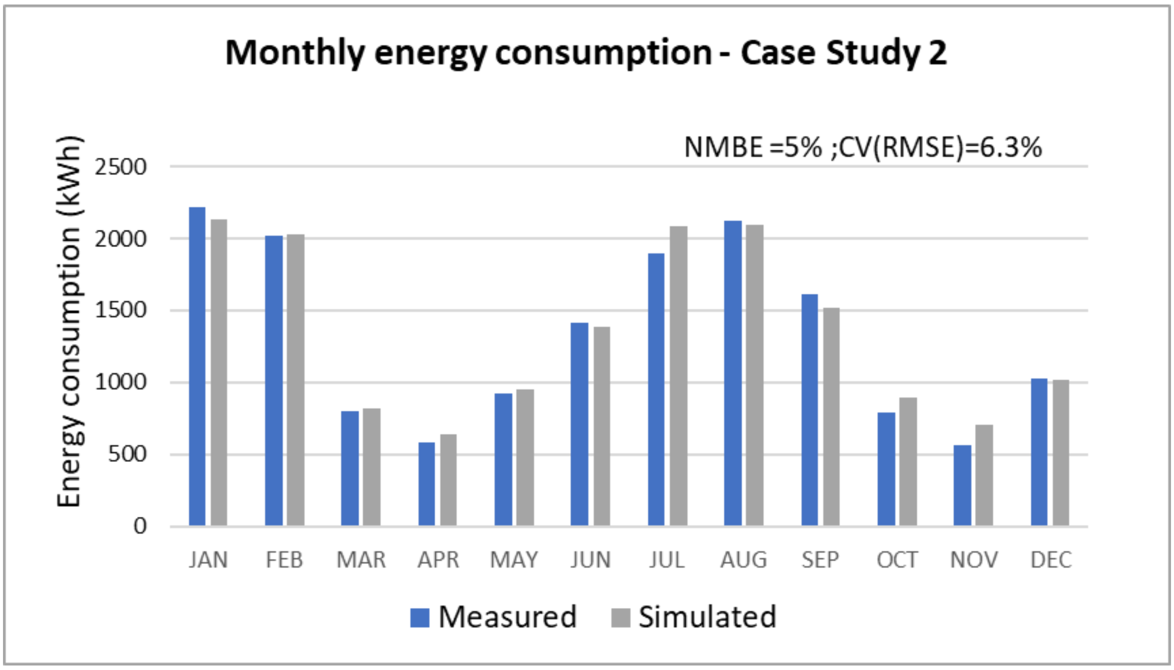


Figure 6. 16 Monthly calibration results for Case Study 2

6.3.3 Hourly Energy Consumption Calibration

Initial checks confirmed that the measured and simulated energy consumption were correlated and in agreement to some extent. This can be seen when comparing the overall trends in measured and simulated energy consumption between 11th July and 13th July 2022 (Figure 6.17). However, an evaluation of hourly NMBE and CV(RMSE) showed a discrepancy between monitored and simulated data.

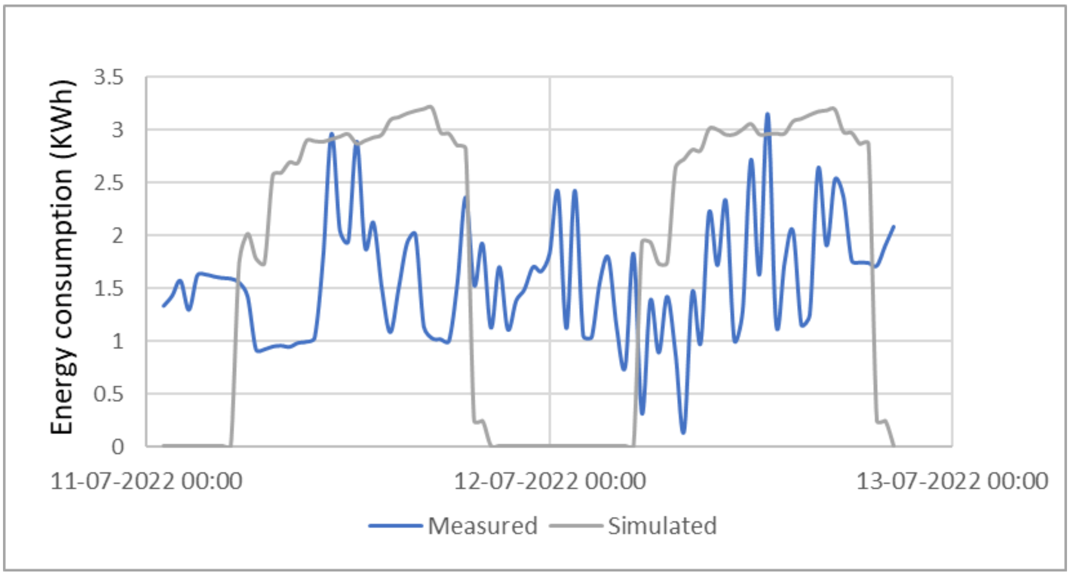


Figure 6. 17 General trend simulated versus monitored energy use data between 11th and 13th July 2022.

The running average of the measured data was used to help smooth its fluctuating pattern and then compared to the running average of the simulation outputs. When comparing the running average of measured energy consumption data of the summer and winter months against the running average of simulated data in Figures 6.18 - 6.19, it is apparent that the general patterns of both are correlated very closely, which facilitates model calibration based on energy consumption using ASHRAE 14 calibration criteria.

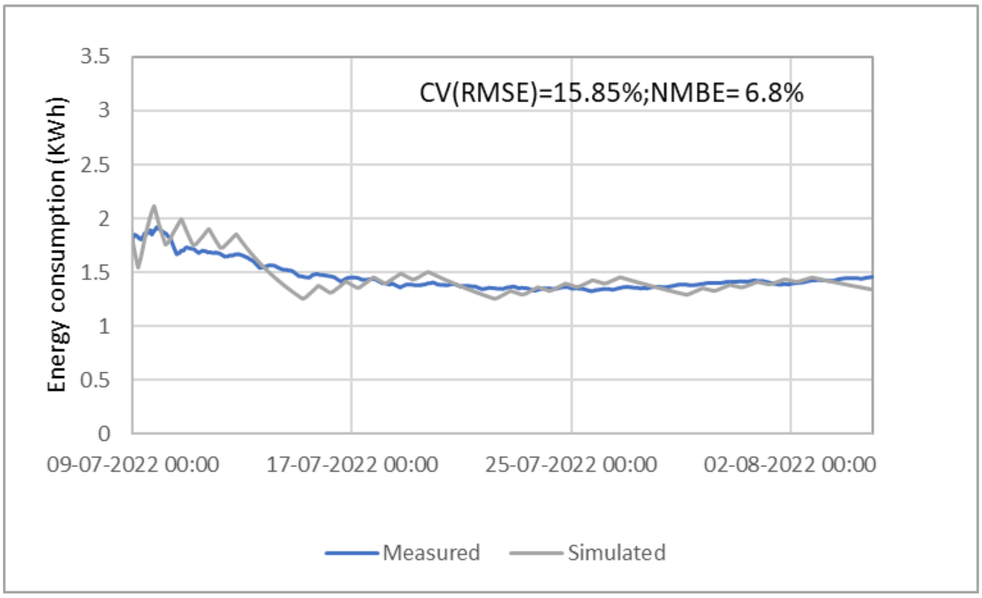


Figure 6. 18 Running average of measured and simulated building energy consumption in one summer month between 9th July 2022 and 5th August 2022.

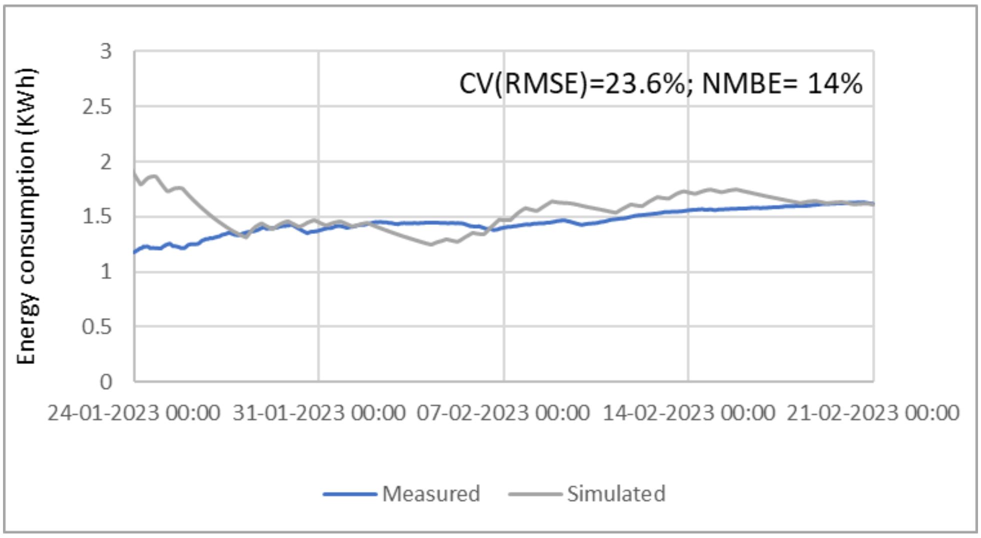


Figure 6. 19 Running average of monitored and simulated building energy consumption in one winter month between 24th January 2023 and 21st February 2023.

6.3.4 Monthly Zone Temperature Calibration

Figure 6.20 shows that the simulated average indoor temperature of selected spaces is in good agreement with the measured average indoor temperature. Moreover, an acceptable CV(RMSE) and NMBE are also achieved for all selected spaces. Thus, the model is considered calibrated based on hourly zone temperature, and the building model is reliable for the simulation study.

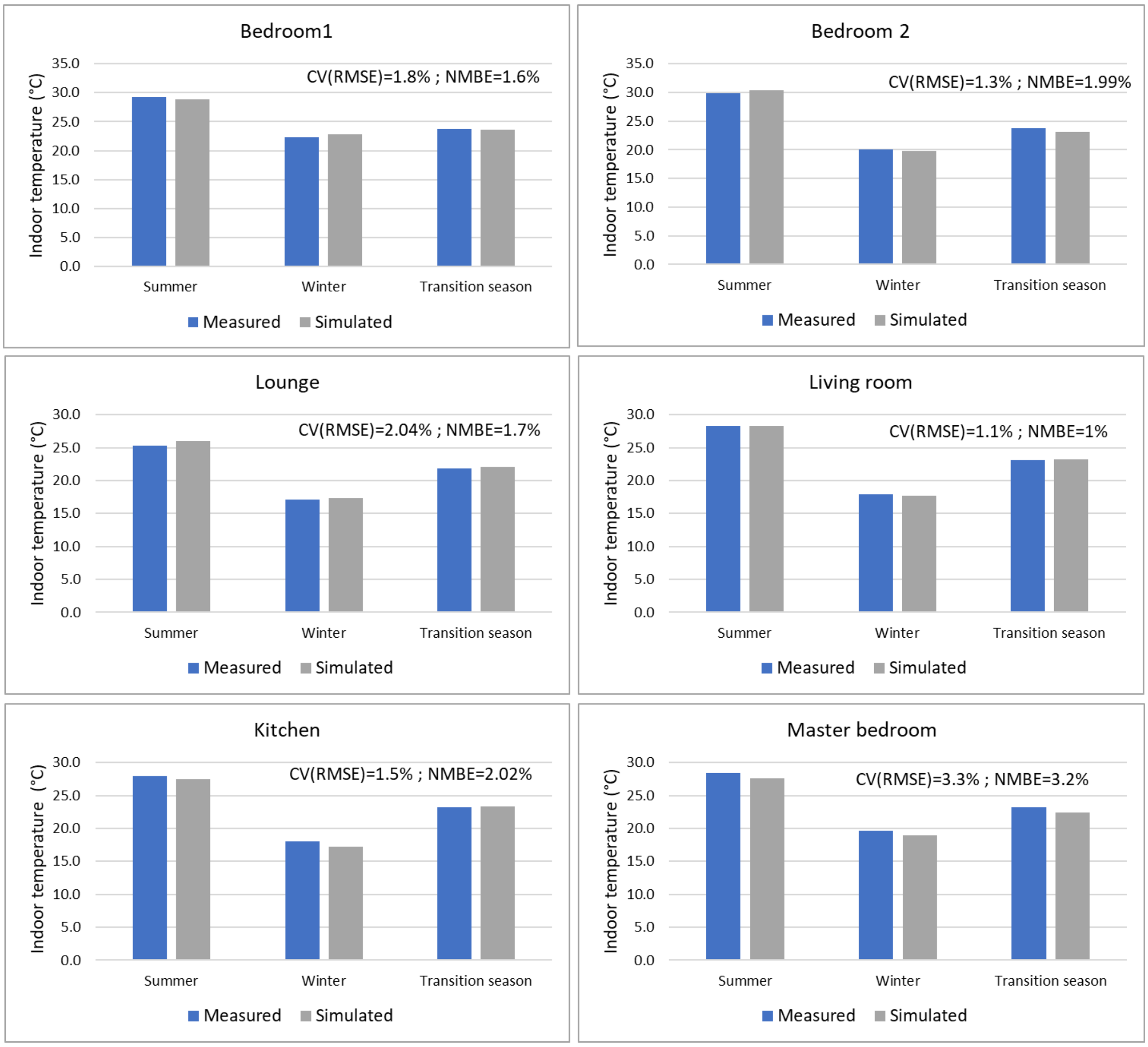


Figure 6. 20 Monthly zone temperature calibration - Case Study 2.

6.3.5 Hourly Zone Temperature Calibration

To further ensure that the calibrated model reasonably represented the actual building's performance, hourly zone temperature calibration was carried out for the summer month studied. The monitored indoor temperature data for selected zones were also compared to the simulated data. The simulated temperatures closely follow the measured air temperature, as shown in Figure 6.21. Moreover, an acceptable hourly NMBE and CV(RMSE) are also achieved for all selected zones.

Therefore, the calibrated model properly reflects the actual building's performance and is validated for the simulation study.

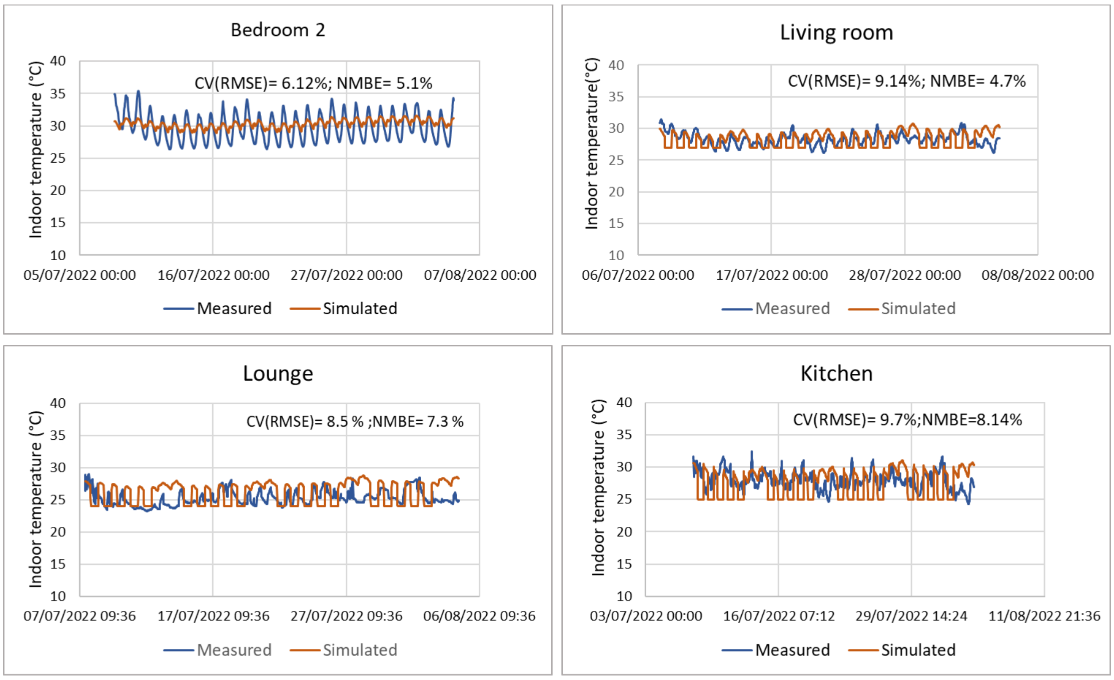


Figure 6. 21 Hourly zone temperature calibration - case study 2.

6.4 Calibration Results for Case Study Building 3

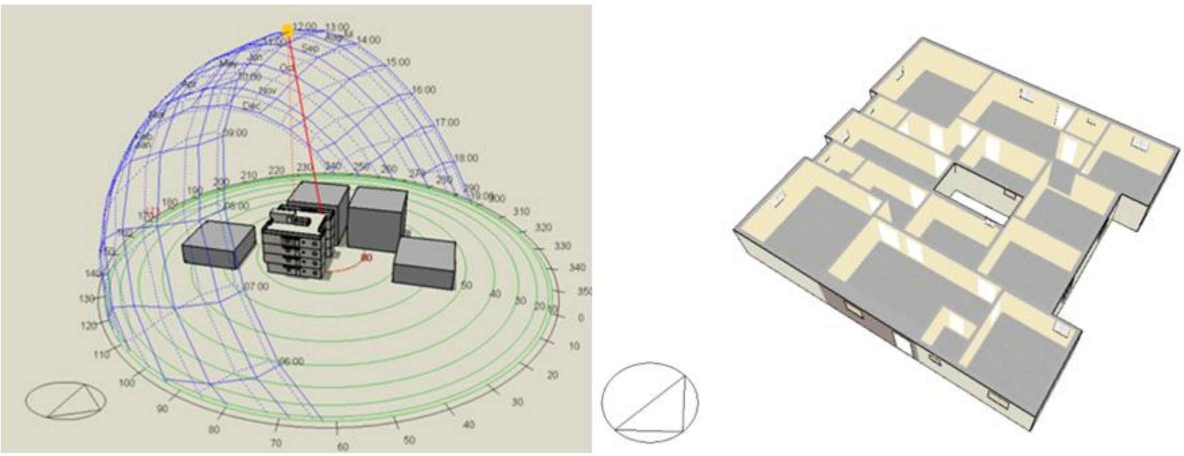


Figure 6. 22 Case study building 3 modelling in DesignBuilder.

6.4.1 Setting Up the Sensitivity Analysis

Cooling load and heating load were set as objective functions for the sensitivity analysis, as they were determined as the key contributors to the energy consumption of case study building 3. The sensitivity test was conducted on 13 parameters to assist the calibration stage by identifying the hierarchical order of the sensitive parameters. Once these parameters had been determined, the values of the least influential parameters were removed from further consideration, and the most influential ones were tuned manually until an acceptable discrepancy between the measured and simulated data was achieved. The number of random simulations was chosen as 100 times the number of design parameters. Table 6.3 shows the parameters that were chosen for sensitivity analysis for case study3.

Table 6. 3 Selected parameters for sensitivity analysis - case study 3.

	parameters	**Distribution category**	**Distribution curve**	**Distribution summary**	**Target objects**
Flat roof construction	**Flat roof construction**	1-Discrete	20-Uniform (Discrete)	Prob: 0.200; Options: 4	Building
External wall construction	External wall construction	1-Discrete	20-Uniform (Discrete)	Prob: 0.167; Options: 4	Building
Ground floor construction	Ground floor construction	1-Discrete	20-Uniform (Discrete)	Prob: 0.167; Options: 6	Building
Glazing type	Glazing type	1-Discrete	20-Uniform (Discrete)	Prob: 0.200; Options: 5	Building
Local shading type	Local shading type	1-Discrete	20-Uniform (Discrete)	Prob: 0.250; Options: 4	Building
Window to wall ratio %	Window to wall ratio %	2-Continuous	Normal	Mean: 40	Building
Equipment power density (w/m²)	Equipment power density (w/m²)	2-Continuous	Normal	Mean: 5	Building
Occupancy (Days/Weeks)	Occupancy (Days/Weeks)	1-Discrete	20-Uniform (Discrete)	Min.Val: 0.00; Step size: 1.00; Step No: 8.00	Building
Cooling system Seasonal COP	Cooling system Seasonal COP	2-Continuous	Normal	Mean: 2.5	Building
Heating system Seasonal COP	Heating system Seasonal COP	2-Continuous	Normal	Mean: 2.5	Building
Cooling set-point temperature (C°)	Cooling set-point temperature (C°)	2-Continuous	Normal	Mean: 25	Building
Heating set-point temperature (C°)	Cooling set-point temperature (C°)	2-Continuous	Normal	Mean: 20	Building
Infiltration rate (ac/h at 50 Pa))	Infiltration rate (ac/h at 50 Pa)	2-Continuous	Normal	Mean: 6	Building

6.4.1.1 Sensitivity Analysis Result

Based on the sensitivity analysis results for Case Study 3 (Figure 6.23), the SRC of the cooling load shows that the most influential design parameter is external wall construction. The figure also shows that ground floor construction, and flat roof construction are another design parameters to which the cooling load is sensitive. Cooling load is moderately influenced by local shading, glazing type and cooling setpoint. Infiltration rate, WWR, cooling system COP, and equipment power density, do not have any notable impact on cooling load and can therefore be ignored in the parameter adjustment step. The heating load sensitivity analysis results illustrate that the external wall construction, and flat roof construction, have the greatest influence on heating load. Glazing type, and heating setpoint have a moderate influence on heating load, ground floor construction, local shading, window-to-wall ratio, heating system coefficient of performance, and equipment power density, have a very limited influence on heating load (Figure 6.24). Adjusting design parameters that have a high influence on cooling and heating loads helps reduce the discrepancy between actual and simulated model results. However, since the U-value specifications of the wall were set based on actual measurements, they were exempt from the parameter adjustment step. Design parameters specifications of the flat roof construction, and ground floor construction, heating and cooling setpoints were tuned manually until an acceptable discrepancy between the monitored and simulated data was achieved.

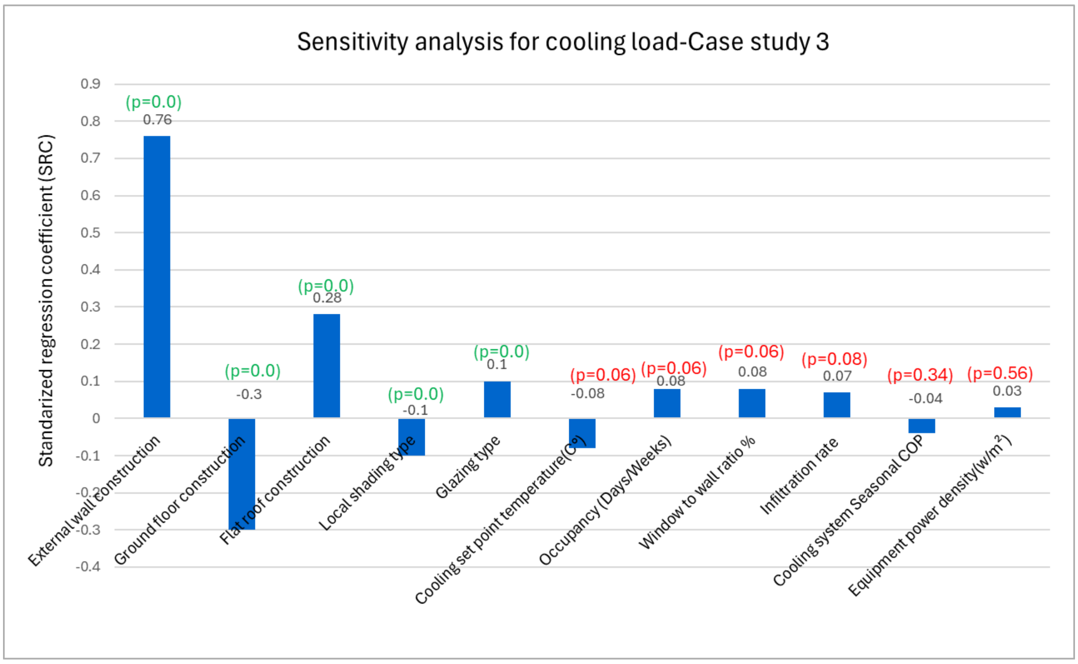


Figure 6. 23 Cooling load sensitivity analysis result - Case Study 3.

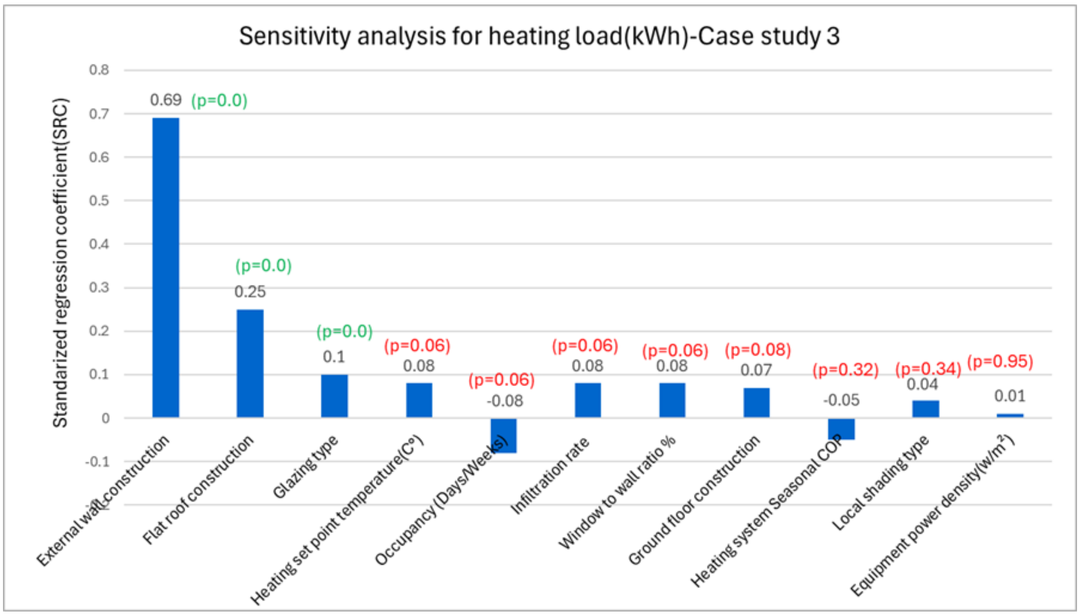


Figure 6. 24 Heating load sensitivity analysis result - Case Study 3.

6.4.2 Monthly Energy Consumption Calibration

Since energy consumption was measured only for one apartment, the energy consumption of the whole building had to be estimated to calibrate the building model. To enable this, a simple shoebox model was developed using actual construction materials and a Benghazi weather file and then placed in three different locations and heights within a compound block. It was placed as shown in Figure 6.25: one at the top of a compound block to represent the top floor apartments (the monitored apartment); one in the middle of two compound blocks to represent the middle-floor apartments; and one under a compound block and adjacent to the ground to represent the ground floor apartments. The simulation was carried out for each position. It was found that the consumption of the second and third floors was 4.67% lower than that of the top floor, while ground floor energy consumption was 9.1 % lower than that of the top floor. Based on this result, the energy consumption of the whole building was estimated and then employed for monthly energy consumption calibration.

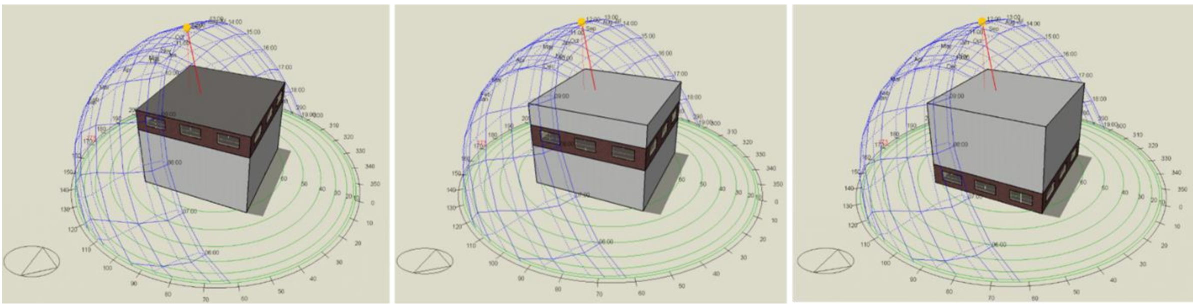


Figure 6. 25 Shoebox energy model to estimate the whole building's energy consumption.

Figure 6.26 compares the monthly simulation results and the measured data for energy consumption and provides the key statistical error values. In line with ASHRAE Guideline 14-2002, the monthly energy use profile was estimated with an acceptable degree of accuracy: i.e., CV (RMSE) < 15% and NMBE < ±5%.

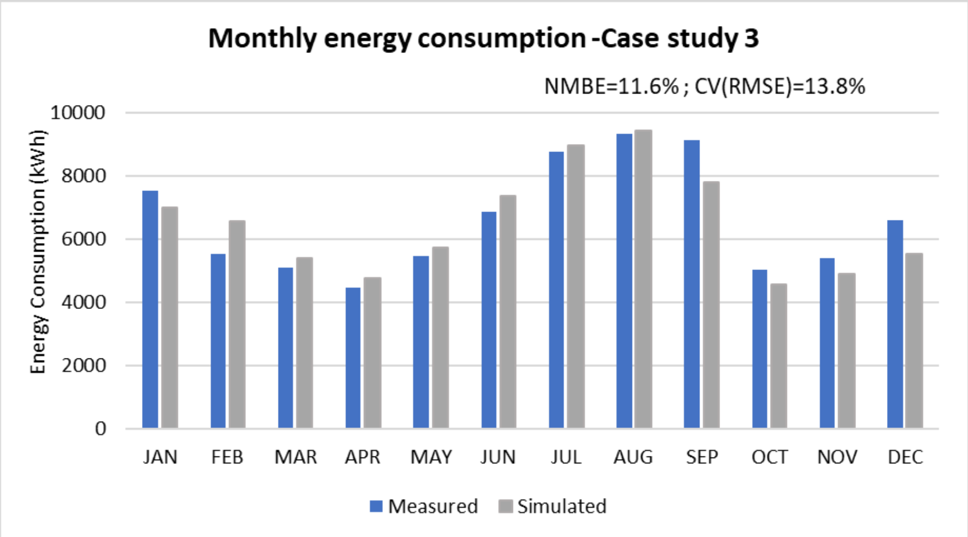


Figure 6. 26 Monthly calibration results for Case Study 3.

6.4.3 Hourly energy consumption calibration

The running average of measured energy consumption data for the summer and winter months is shown against the running average of simulated data in Figures 6.27- 6.28, revealing that the general patterns of each are correlated very closely, which facilitates model calibration based on energy consumption using ASHRAE 14 calibration criteria.

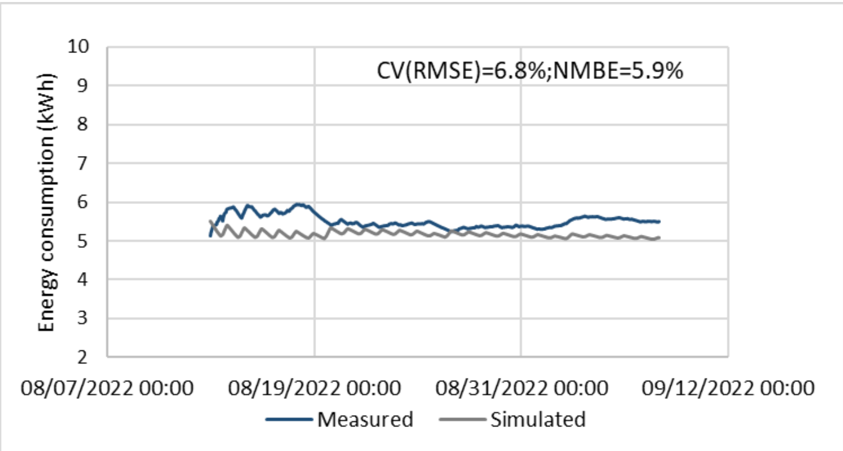


Figure 6. 27 Running average of measured and simulated building energy consumption in one summer month between 11th August 2022 and 7th September 2022.

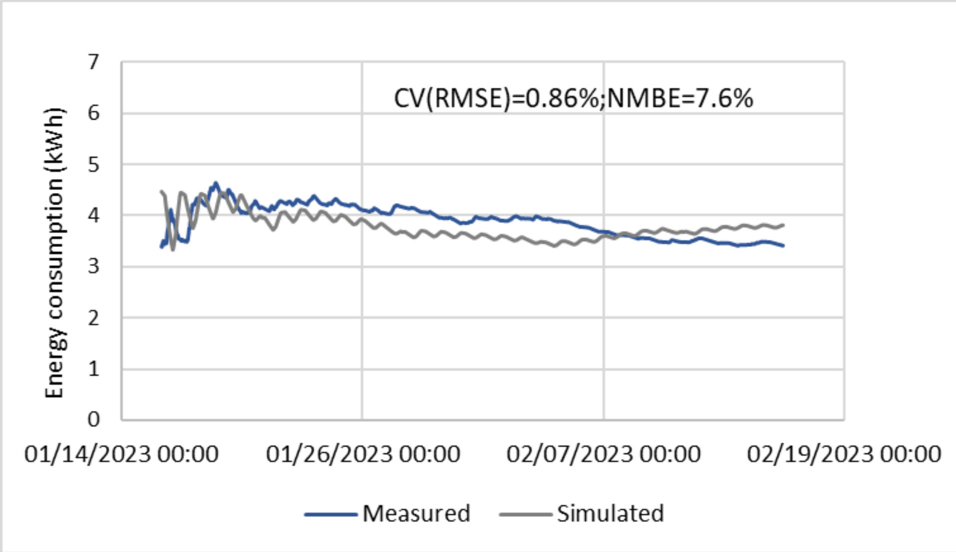


Figure 6. 28 Running average of measured and simulated building energy consumption in one winter month between 15th January 2023 and 15th February 2023

6.4.4 Monthly zone temperature calibration

Zone temperature calibration was also carried out on this model to ensure that the calibrated model properly reflected the actual building's performance. Figure 6.29 shows that the simulated average indoor temperatures for randomly selected spaces in the upper flat spaces closely follow the measured average indoor temperature. Moreover, an acceptable CV(RMSE) and NMBE are also achieved for all selected zones. Thus, the model is considered calibrated based on monthly zone temperatures.

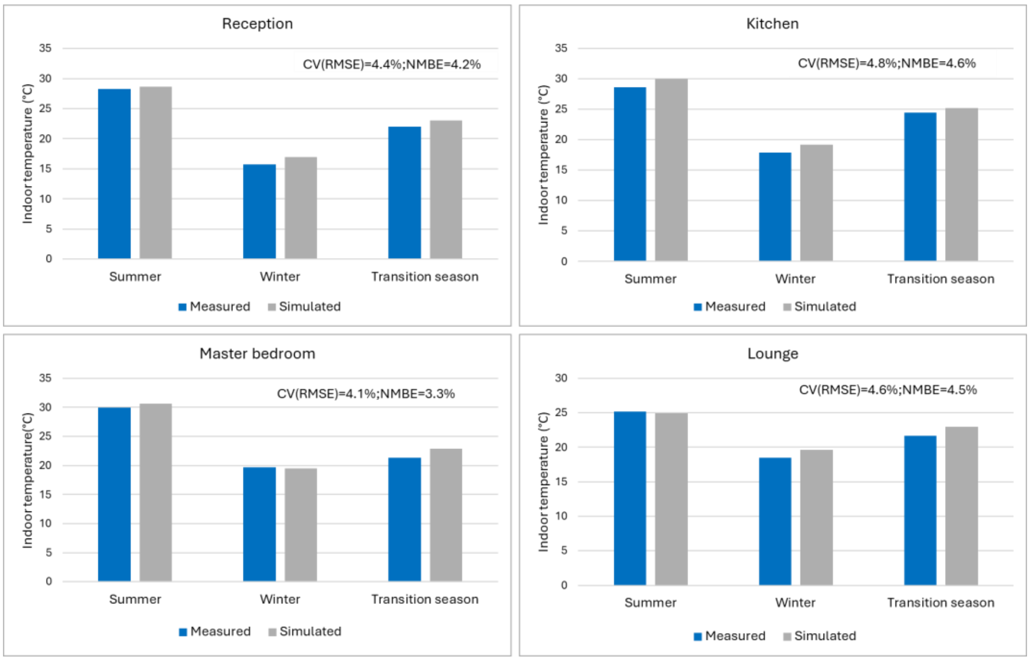


Figure 6. 29 Monthly zone temperature calibration of indoor spaces - case study 3.

6.4.5 Hourly zone temperature calibration

To further ensure that the calibrated model reasonably represented the actual building's performance, hourly zone temperature calibration was carried out for the summer month. Monitored indoor temperature data for selected zones were also compared to the simulated data. The simulated temperatures closely follow the measured air temperature, as shown in Figure 6.30. Moreover, an acceptable hourly NMBE and CV(RMSE) were also achieved for all selected zones. This demonstrates that the calibrated model properly reflects the actual building's performance, and it is validated for the simulation study.

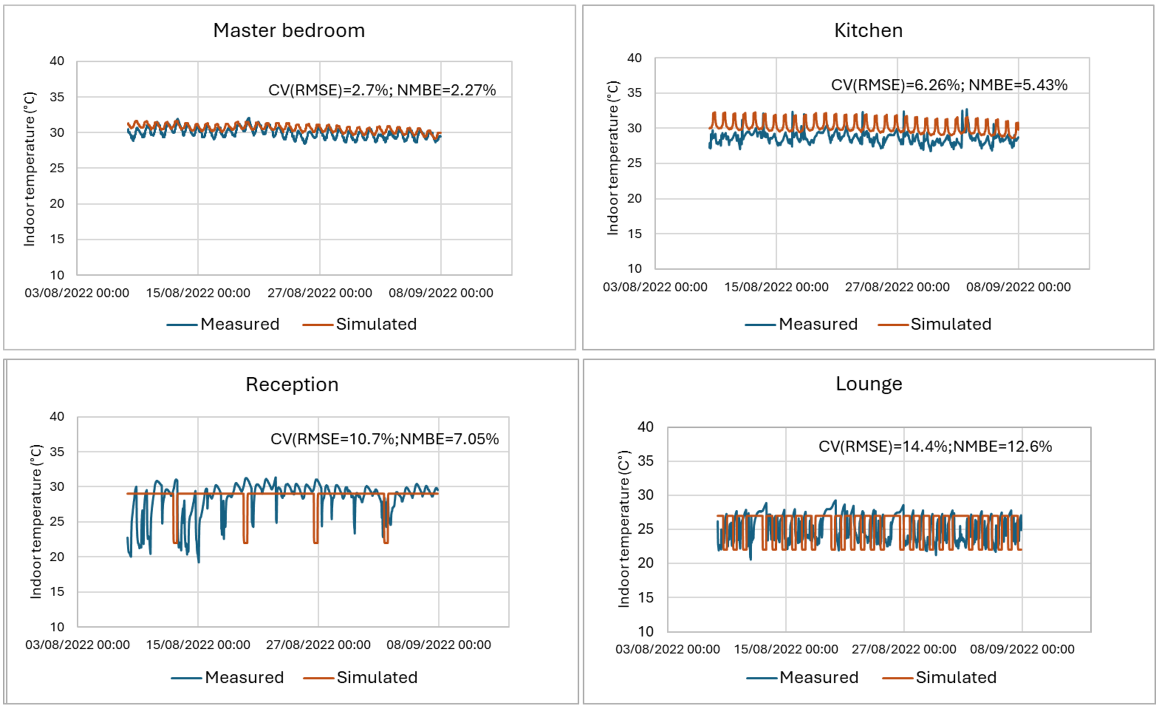


Figure 6. 30 Hourly zone temperature calibration for ground floor spaces.

6.5 Chapter Summary

This chapter has discussed the application of monthly and hourly calibration simulations to develop reliable simulation models using input data collected during the building survey and monitoring stage. Three different residential types; a terraced house, detached house, and apartment building were calibrated. Their performances were assessed based on the statistical metrics specified by ASHRAE Guideline 14-2002, showing an acceptable level of validity. The statistical indices used for model accuracy are normalised mean bias error (NMBE), and coefficient of variation of the root mean squared error (CV(RMSE)). The existing building models were calibrated by modifying specific simulation input parameters identified by sensitivity analysis until an acceptable level of accuracy was achieved. In Chapter 7, the calibrated building models are firstly used to investigate the different passive measures via parametric analysis. A combination of these retrofit measures is then studied via a multi-objective optimisation method. Finally, the modelled case study buildings are employed to investigate the potential for meeting energy needs by integrating renewable energy sources to achieve the target of net zero energy buildings (NZEBs).

Chapter 7: Building Simulation and Optimisation Study - Results and Discussion

7.1 Introduction

The first section of this chapter presents the annual simulation results for the base case building models in DesignBuilder. Heat balance reports for both summer and winter seasons are studied. The simulation results reveal that the greatest contributors to cooling and heating loads are heat gain and loss through the building's envelope. Therefore, in Section Two, the calibrated models from DesignBuilder are used to numerically evaluate the effects of upgrading the envelope parameters of each case study building through the implementation of different single retrofit measures. Passive retrofit measures include roof insulation, external wall insulation, ground floor insulation, an energy efficient glazing system, and window shading. With a view to reducing the embodied carbon associated with building retrofit, biobased materials including sheep's wall, camel hair, hemp fibres, and data palm fibres are employed in this study.The most effective retrofit measures are then employed to conduct multi-objective optimisation to determine the optimal combination between the different measures in terms of energy use reduction while maintaining comfortable indoor thermal conditions. A further study is carried out on the optimised case study building models to explore the potential to achieve the requirements of net zero energy buildings.

7.2 Base Case Simulation Results

7.2.1 Annual Energy Consumption Simulation Results

7.2.1.1 Case Study 1

The simulation results for Case Study 1 show that a typical terraced house located in Benghazi in Libya consumes 24660.97 kWh/y of energy. The house consumes 13198 kWh/y of cooling energy and 4801.78 kWh/y of heating energy to make up the majority of the consumed energy.The annual primary energy demand is 209 kWh/m²/y, which is above the 135 kWh/m²/y of the Passivhaus retrofit target. The annual primary cooling and heating energy demand is 124.21 kWh/m²/y, which is about four times higher than the 30 kWh/m²/y of the Passivhaus retrofit target. These data are used as a reference for comparing with the building energy optimisation results provided later in this chapter. The total energy end uses in Figure 7.1 shows that building cooling and heating are the largest contributors to consumed energy.

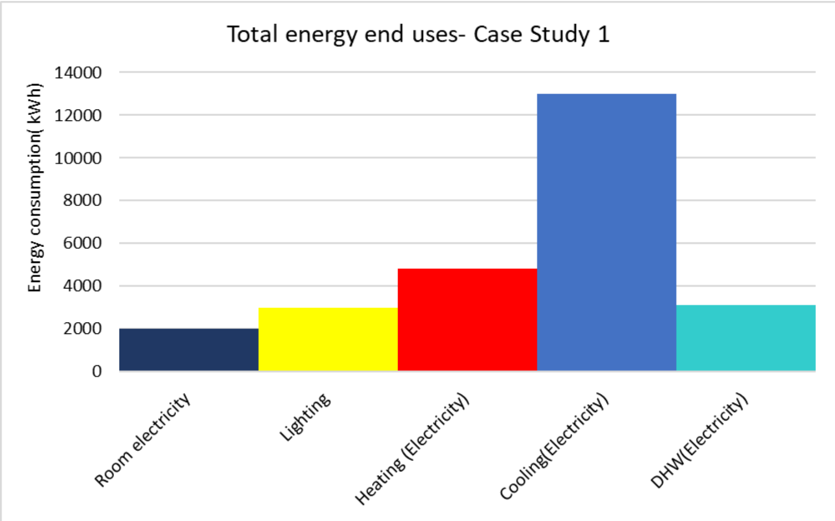


Figure 7. 1 Energy end uses - Case Study 1

7.2.1.2 Case Study 2

The simulation results for Case Study 2 show that a typical detached house (villa) located in Benghazi consumes 17541.33 kWh/y of energy. The house consumes 9259.82 kWh/y of cooling energy and 2961.52 kWh/y of heating energy to make up the majority of the consumed energy. The annual primary energy demand is 226 kWh/m²/y, which is above the 135 kWh/m²/y of the Passivhaus retrofit target. The annual primary cooling and heating energy demand is 122.1 kWh/m²/y, which is about four times higher than the 30 kWh/m²/y of the Passivhaus retrofit target. These data are used as a reference for comparing with the building energy optimisation results given later in this chapter. The total energy end uses in Figure 7.2 shows that building cooling and heating are the largest contributors to consumed energy.

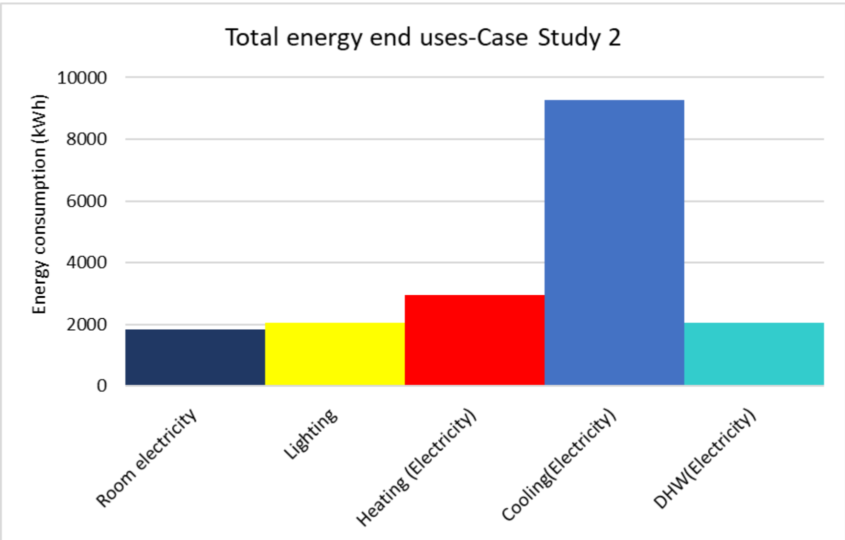


Figure 7. 2 Energy end uses - Case Study 2

7.2.1.3 Case Study 3

The simulation results for Case Study 3 shows that a typical apartment building located in Benghazi consumes 78111.28 kWh/y of energy. The house consumes 41768.16 kWh/year of cooling energy and 12122.29 kWh/year of heating energy to make up the majority of the consumed energy. The annual primary energy demand is 179.54 kWh/m²/y, which is above the 135 kWh/m²/y Passivhaus retrofit target.The annual primary cooling and heating energy demand is about 93.32 kWh/m²/y which is about three times higher than the 30 kWh/m²/y target of the Passivhaus retrofit target. These data are used as a reference for comparing with the building energy optimisation results provided later in this chapter. The total energy end uses in Figure 7.3 show that building cooling and heating constitute the largest consumers of energy.

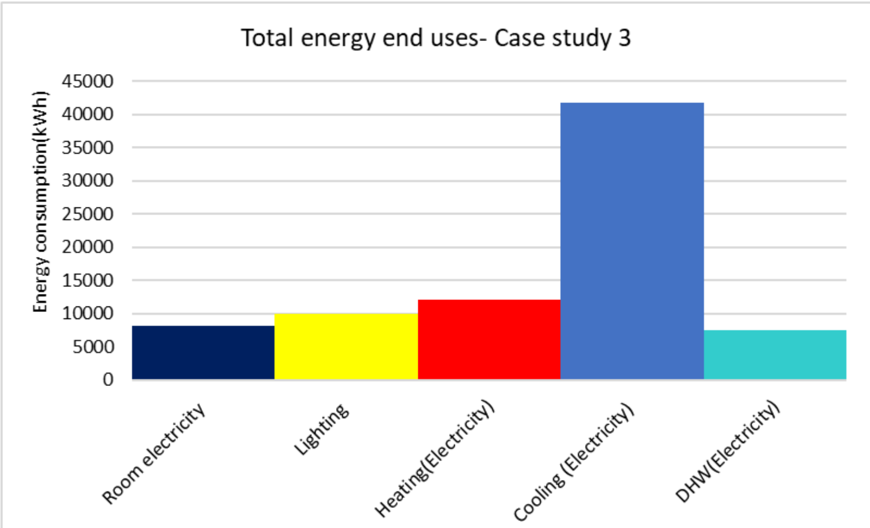


Figure 7. 3 Energy end uses - Case Study 3

7.2.2 Heat Balance Simulation Results

7.2.2.1 Heat Balance Result - Case Study 1

The summer heat balance graph for Case Study 1 shows that the highest heat gains occur through the roof, followed by the walls and then solar gain from exterior windows. The internal heat gain from occupants, electrical lighting, appliances, and infiltration rate is limited compared to external heat gain (Figure 7.4). The graph also shows that there is heat loss through the ground floor. The winter heat balance graph illustrates that the roof and walls are the most influential parameters on heating load (Figure 7.5). Heat loss is also observed through the ground floor. The heat balance results are consistent with the sensitivity analysis results, which show that building envelope parameters are the most influential parameters for cooling load in summer and heating load in winter. Therefore, thermal refurbishment of the building envelope parameters could reasonably be expected to lead to a reduction in building energy use and its associated influence on the environment.

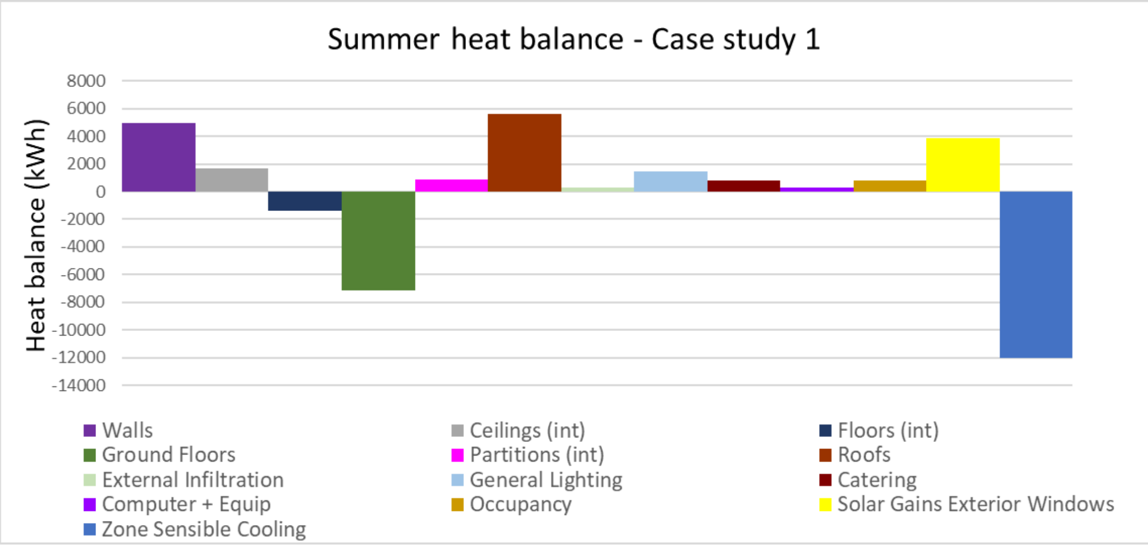


Figure 7. 4 Heat balance report for summer - Case Study 1.

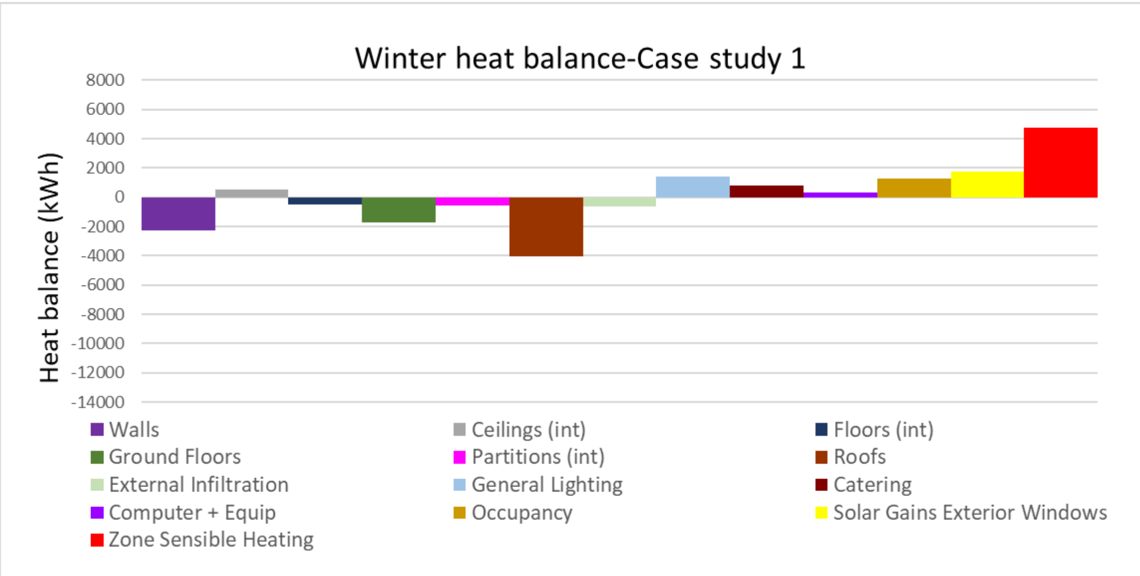


Figure 7. 5 Heat balance report for winter- Case Study 1.

7.2.2.2 Heat Balance Result - Case Study 2

The summer heat balance graph for Case Study 2 shows that the highest heat gains occur through the external wall construction and the roof construction, followed by solar gain from exterior windows. The internal heat gain from occupants, electrical lighting, appliances, and infiltration rate is limited compared to external heat gain (Figure 7.6). The graph also shows that there is heat loss through the ground floor. On the other hand, the winter heat balance graph illustrates that heat loss through the ground floor, the roof, and the walls are the most influential parameters affecting heating load (Figure 7.7).These heat balance results are consistent with the sensitivity analysis results, which show that the building envelope parameters are the most influential parameters on cooling load in summer and heating load in winter. Consequently, thermal refurbishment of the building envelope parameters could lead to a reduction in building energy use and associated environmental impacts.

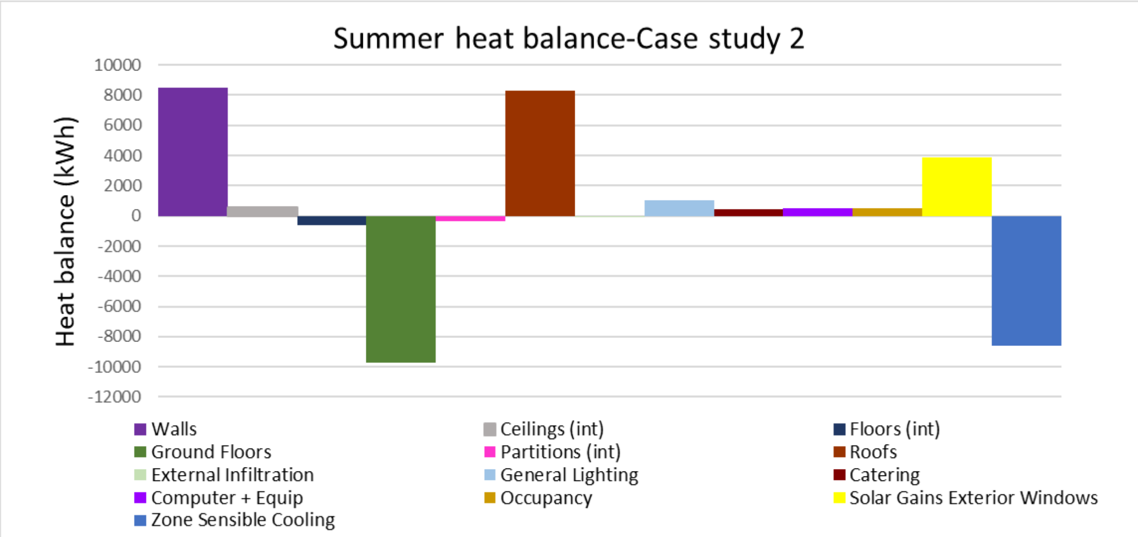


Figure 7. 6 Heat balance report for summer - Case Study 2.

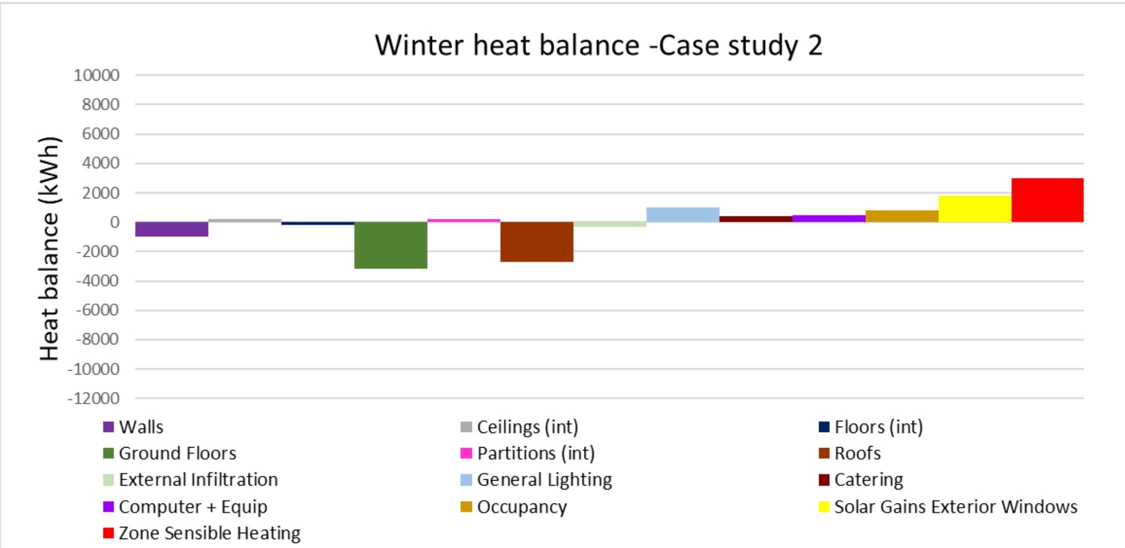


Figure 7. 7 Heat balance report for winter - Case Study 2.

7.2.2.3 Heat Balance Result - Case Study 3

Based on the summer heat balance graph for Case Study 3, the highest heat gains are seen through the external wall construction, followed by solar gain from exterior windows and then the roof. The graph also shows that there is heat loss through the ground floor. The internal heat gain from occupants, electrical lighting, appliances, and infiltration rate is limited compared to external heat gain (Figure 7.8). The heat balance graph for winter illustrates that heat loss through the external walls is the most influential parameter for heating load, and that the roof and ground floor construction have a medium influence on heating loss (Figure 7.9). The heat balance results are consistent with the sensitivity analysis results, which show that the building envelope parameters are the most influential parameters for cooling load in summer and heating load in winter. Accordingly, thermal refurbishment of the building envelope parameters could plausibly lead to a reduction in building energy use and its associated influence on the environment.

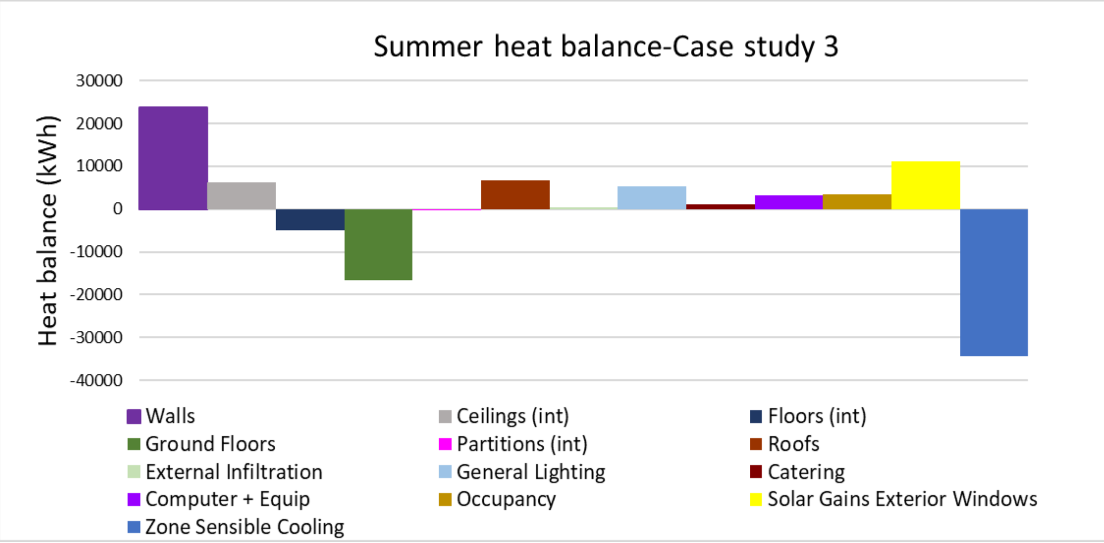


Figure 7. 8 Heat balance report for summer - Case Study 3.

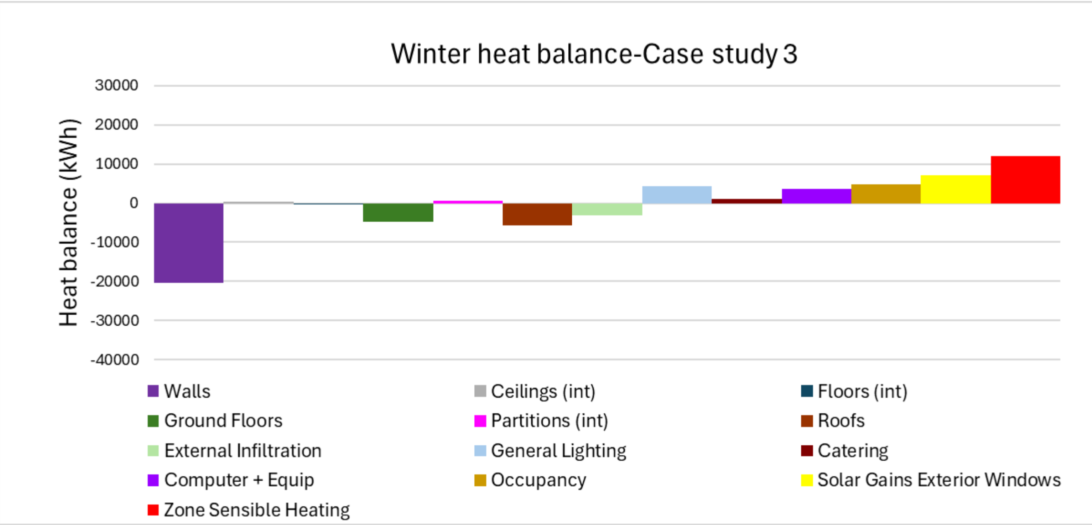


Figure 7. 9 Heat balance report for winter - Case Study 3.

7.3 Case Study Model Optimisation Result

A hybrid optimisation approach is employed to numerically optimise the energy performance of the case study building models. Single and combined passive retrofit measures are employed firstly to identify the optimal measures for improving buildings' energy performance without compromising thermal comfort. A further study is conducted to investigate the potential for meeting the energy consumption of the optimised models by installing photovoltaic systems to achieve the requirements of net zero energy buildings. Accordingly, the optimisation simulation study is divided into three sequential stages. In stage 1, different passive retrofit measures are investigated individually to determine the impact of each single measure in reducing buildings energy use. Passive retrofit measures include roof insulation, external wall insulation, ground floor insulation, an energy efficient glazing system, and window shading. The evaluation of each single measure is primarily based on reduction in cooling and heating energy consumption. The percentage of comfort hours is assessed based on the acceptable limits as stated in ASHRAE 55, ranging from 80% to 90% using DesignBuilder outputs. In stage 2, combined passive retrofit measures are investigated via the multi-objective optimisation tool in DesignBuilder to identify a range of optimal solutions that achieve a compromise between energy consumption and thermal comfort. The optimal solutions are assessed against the Passivhaus targets for retrofits. Stage 3 investigates the effectiveness of on-site energy generation in meeting the target of NZEBs.

7.3.1 Case Study 1- Optimisation Results

7.3.1.1 Stage 1 Optimisation Results

7.3.1.1.1 Roof Insulation

This section examines the impact of upgrading the base case roof with biobased insulation materials. The existing roof of Case Study 1 has a U-value of 3.09 W /m²K. The U-values selected for optimising the roof range between 0.5 W/m²K and 0.1 W/m²K in 0.1 decrements. The analysis also considers the effect of the insulating materials' position, both inside and outside. The specifications of the optimised roof with insulation materials at different thicknesses are described in Table 4.14 in the Methodology Chapter.

Influence of Roof Insulation on Cooling and Heating Energy Consumption

Figure 7.10 demonstrates the influence of roof insulation on cooling and heating energy. Reducing the thermal transmittance (U-value) of the roof by adding biobased insulation leads to a decrease in cooling and heating energy. Reducing the base case U-value of the roof to 0.5 W/m²K through internal insulation reduces the cooling and heating energy by 20.5% and 36.15%, respectively. Cooling and heating energy continue to decline as the U-value is reduced further, reaching 25.3% and 43.3% respectively at a U-value of 0.1 W/m²K. External insulation has slightly more influence on cooling energy and marginally less on heating energy compared to internal insulation, where a U-value of 0.5 W/m²K reduces the cooling energy by 21.7% and heating energy by 35.8%. As the U-value is decreased further, to 0.1 W/m²K, cooling energy is reduced by 25.7% and heating energy is reduced by 43.2%. Accordingly, the position of the insulation material, whether internal or external, does not substantially impact energy use reduction. The variation between insulation materials in terms of energy reduction is minor and cannot be seen in the figure, as the four insulating materials achieve relatively similar percentage reductions in cooling and heating energy. This is because the insulation materials have similar thermal properties.

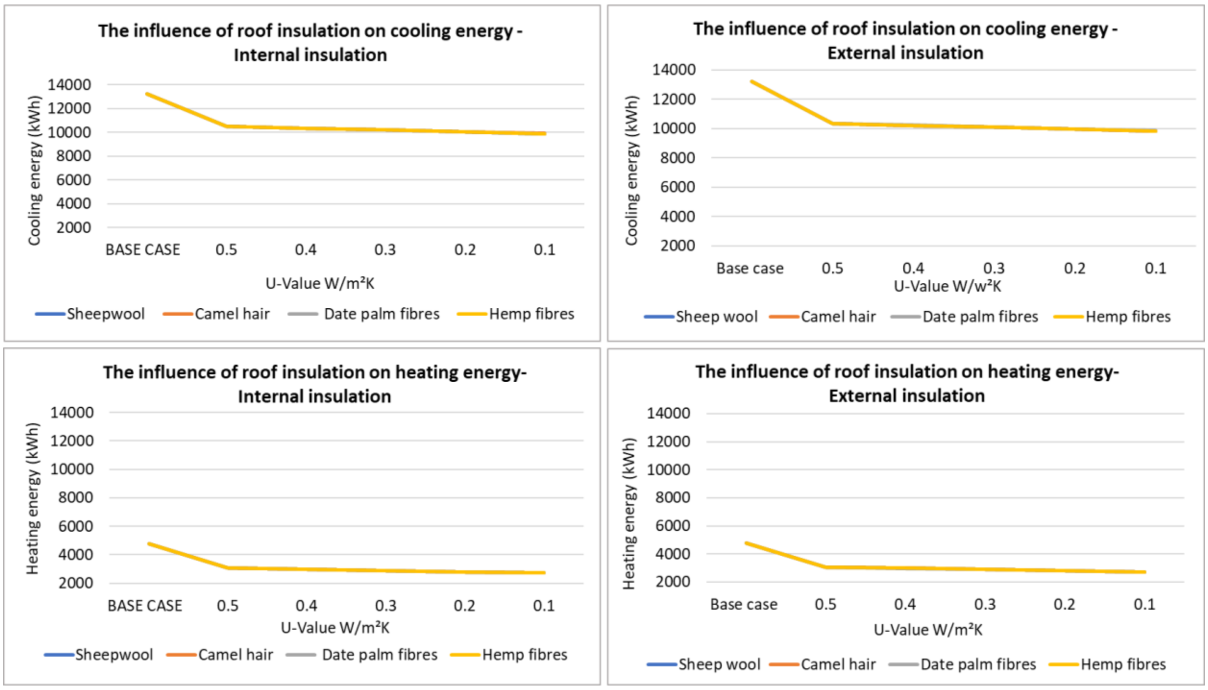


Figure 7. 10 Influence of roof insulation on cooling and heating energy consumption

Influence of Roof Insulation on the Percentage of Comfort Hours in Summer and Winter.

Figure 7.11 shows that the percentage of comfort hours of the base case model in summer and winter fall within the acceptable limits set by ASHRAE 55. In addition, regardless of whether the insulation materials are applied internally or externally, their impact on the percentage of comfort hours is unnoticeable during the summer and winter.

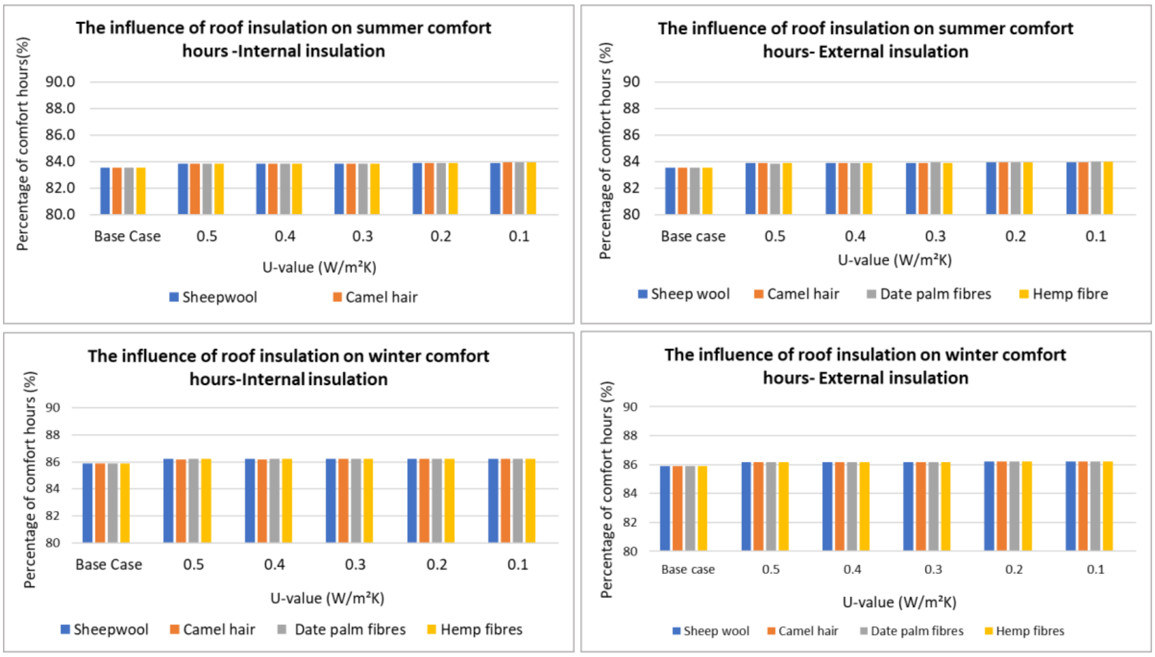


Figure 7. 11 Influence of roof insulation on the percentage of comfort hours during summer and winter

Influence of roof Insulation on Indoor Temperature in Summer and Winter

Although roof insulation does not show an effect on the percentage of comfort hours, it does affect the indoor temperature of the unconditioned spaces in the summer and winter (Figure 7.12). For instance, during summer, the master bedroom on the first floor witnesses a decrease in indoor temperature of 2.5 °C and 3 °C respectively at a roof U-value of 0.5 W/m²K and 0.1 W/m²K, and this decrease brings down the indoor temperature to the upper limit of the comfort zone. On the other hand, an increase in indoor temperature of up to 1.2°C is achieved at a U-value of 0.1 W/m²K in the winter. This means that insulating the roof alone cannot bring the indoor temperature to within comfort levels even when the U-value of the roof is reduced to 0.1 W/m²K.

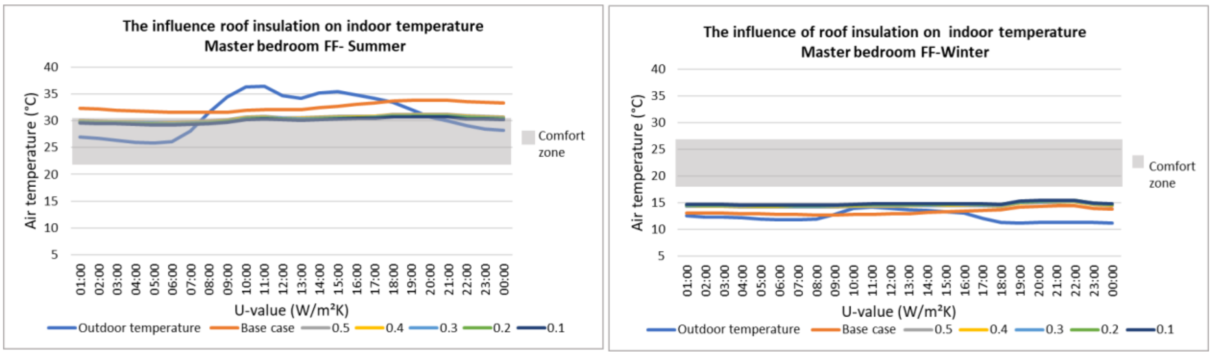


Figure 7. 12 Influence of roof insulation on indoor temperature in summer and winter

7.3.1.1.2 External Wall Insulation

Following the investigation of the potential for savings on cooling and heating energy using roof insulation, this section examines the impact of upgrading the walls with insulation materials. The existing walls have U-values of 2.27 W/m²K for the ground floor walls, and 2.61 W/m²K for first floor walls. The U-values selected for optimising the building walls range between 0.5 W/m²K and 0.1 W/m²K at 0.1 decrements. The specifications of the optimised walls with insulation materials at different thicknesses are described in Table 4.14 in the Methodology Chapter.

Influence of External Wall Insulation on Cooling and Heating Energy Consumption

External wall insulation as shown in Figure 7.13 contributes to reduction in cooling and heating energy consumption. Reducing the base case U-value of the walls to 0.5 W/m²K through internal insulation reduces cooling energy by 15.87%. The reduction in cooling energy continues as the U-value is reduced further, to 21.27% at a U-value of 0.1 W/m²K. External application of wall insulation has slightly more effect than internal insulation on cooling energy, in which about 16.4% and 21.4% reduction is achieved at wall U-values of 0.5 W/m²K and 0.1 W/m²K, respectively. Using internal and external insulation, heating energy is decreased by 14.8 % and 15.7 % at a wall U-value of 0.5 W/m²K, and this decrease continues as insulation thickness is increased to up to 18 % and 18.6% respectively with internal and external insulation at a wall U-value of 0.1 W/m²K. Consequently, implementing wall insulation is effective in reducing energy consumption regardless of whether it is applied internally or externally. The variation between insulation materials in terms of energy reduction is minor and cannot be seen in the figure, as the four insulating materials achieve relatively similar percentage reductions in cooling and heating energy. This is because the insulation materials have similar thermal properties.

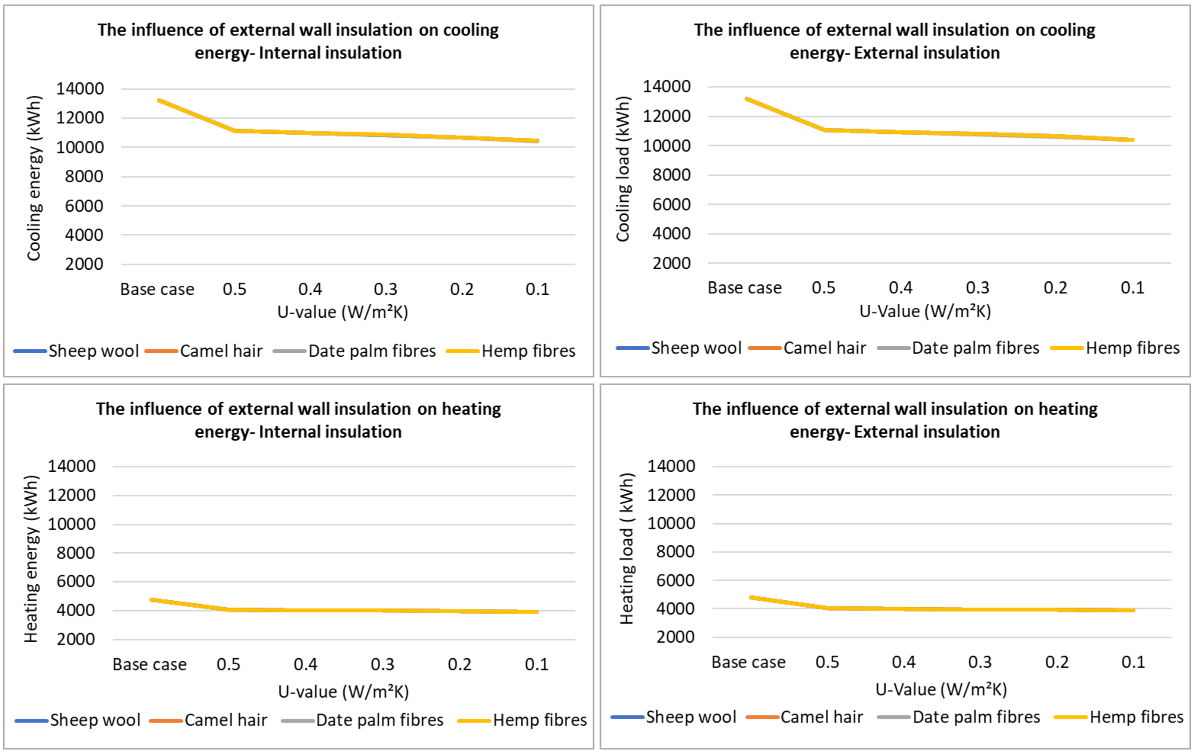


Figure 7. 13 Influence of wall insulation on cooling and heating energy consumption

Influence of External Wall Insulation on Comfort Hours in Summer and Winter

Regarding the thermal conditions of indoor spaces during the summer and winter, during summer, whether wall insulation material is placed internally or externally, no change can be seen in the percentage of comfort hours, and these remain stable within the acceptable limits set by ASHRAE 55 (Figure 7.14). In winter, the percentage of comfort hours is improved slightly whether the insulation is placed internally or externally, but only a 1% increase in the comfort hours is achieved at a U-value of 0.5 W/m²K. A decrease in U-values to 0.1 W/m²K does not show any further improvement in the percentage of comfort hours during winter.

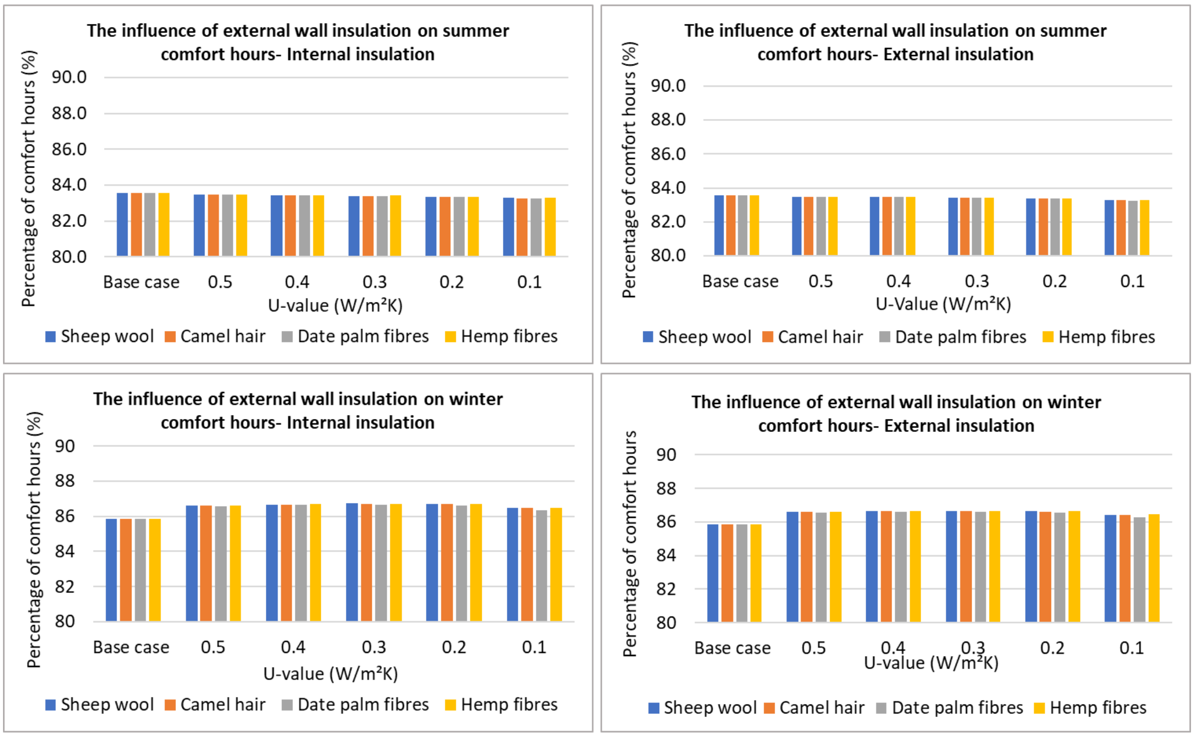


Figure 7. 14 wall insulation influence on the comfort hours during summer and winter

Influence of External Wall Insulation on Indoor Temperature in Summer and Winter

As illustrated in Figure 7.15, insulating the external walls leads to no important change in the indoor temperature of the master bedroom during the summer, and it remains above comfort levels. During the winter, an approximately 1°C increase in indoor temperature is witnessed at a wall U-value of 0.1 W/m²K. However, the temperature is still below comfort levels.

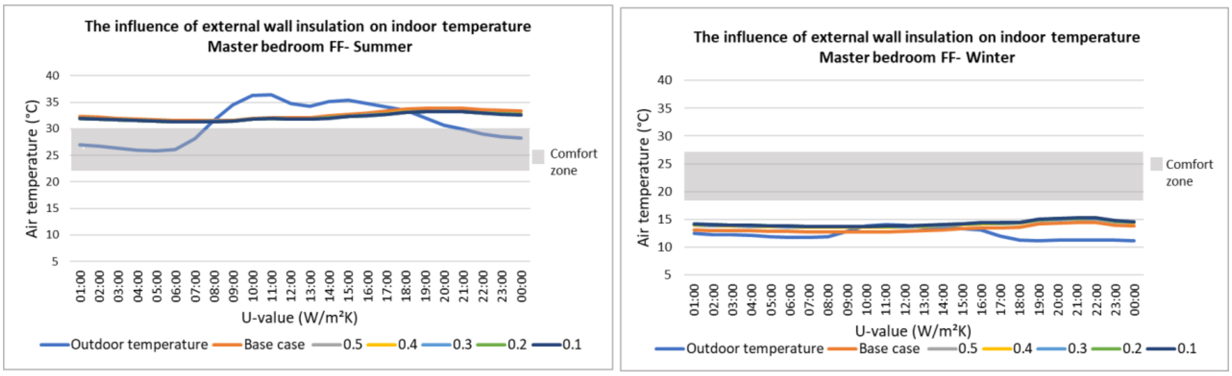


Figure 7. 15 The influence of external wall insulation on indoor temperature in summer and winter

7.3.1.1.3 Ground Floor Insulation

This section involves an investigation of the influence of insulation materials when applied to the internal surface of the ground floor. The existing ground floor of Case Study 1 has a U-value of 1.5

W/m²K. The U-values selected for optimising the internal surface of the ground floor range between 0.5 W/m²K and 0.1 W/m²K in 0.1 decrements. The specifications of the optimised ground floor slabs with insulation materials at different thicknesses are described in Table 4.14 in the Methodology Chapter.

Influence of Ground Floor Insulation on Cooling and Heating Energy Consumption

Ground floor insulation, as shown in Figure 7.16, contributes to an increase in cooling energy, in which an approximately 13.09% increase in cooling energy is witnessed at a floor U-value of 0.5 W/m²K. The increase in cooling energy continues with increase in insulation material to reach 19.3% at a U-value of 0.1 W/m²K. This increase in cooling energy occurs because the ground acts as a heat sink without insulation materials, and insulating the floor leads to increase the cooling energy. In contrast, heating energy is decreased by only 2.6% at a floor U-value of 0.5 W/m²K. As the U-value decreases further, to 0.1 W/m²K, the heating energy is decreased more by up to 3.9%. Thus, because the increase in cooling energy is much greater than the decrease in heating energy, it is not recommended to insulate the floor, but rather to keep it uninsulated to utilise the thermal mass of the floor and help reduce the cooling energy in the summer. Therefore, ground floor insulation is exempted from the multi-objective optimisation stage.

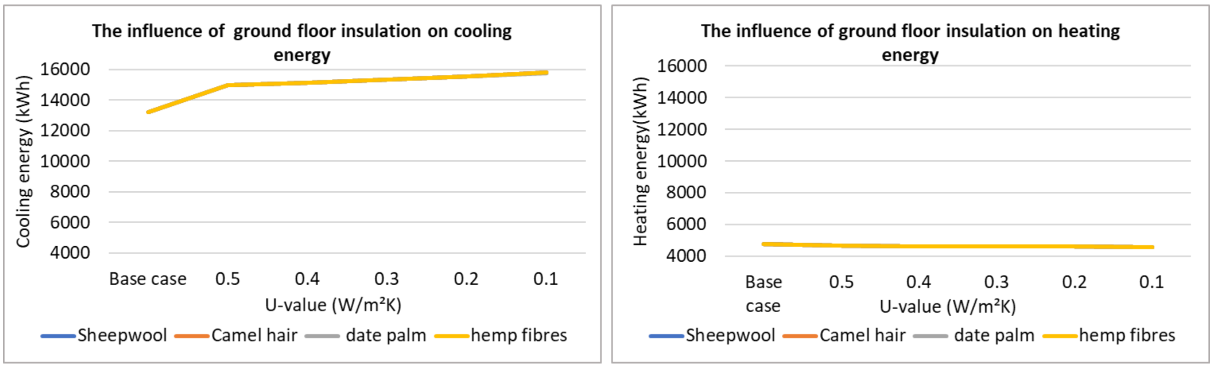


Figure 7. 16 Influence of ground floor insulation on cooling and heating energy consumption

Influence of Ground Floor Insulation on Comfort Hours in Summer and Winter

Considering indoor thermal conditions during the summer, there is only 1% decrease in the percentage of comfort hours witnessed with ground floor insulation at a U-value of 0.1 W/m²K. On the other hand, insulating the ground floor does not show an influence during the winter, and the percentage of comfort hours remains stable and within the acceptable limit as set by ASHRAE 55 (Figure 7.17).

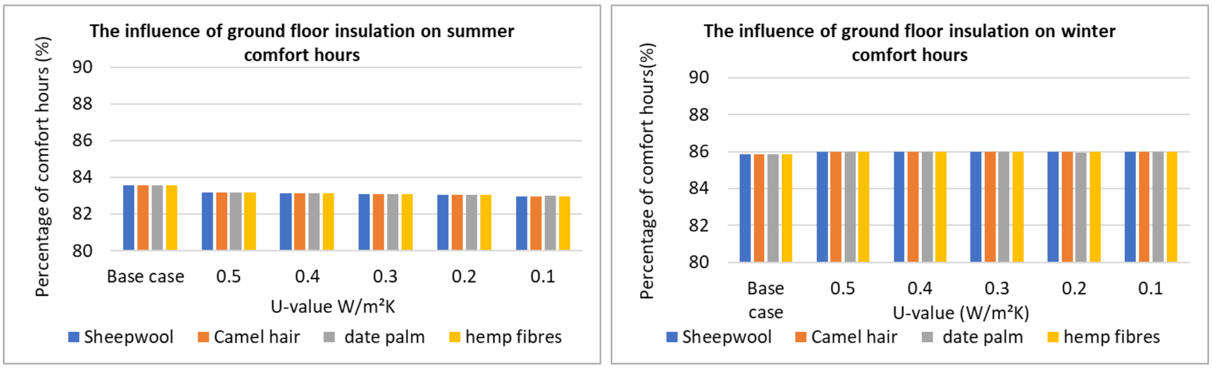


Figure 7. 17 Influence of ground floor insulation on comfort hours during summer and winter

Influence of Ground Floor Insulation on Indoor Temperature in Summer and Winter

Insulating the ground floor has a noticeable impact on indoor temperatures on the ground floor during summer only (Figure 7.18). The temperature of the living room on the ground floor, for instance, witnesses an increase of 2.5 °C and 3.5 °C at a floor U-value of 0.5 W/m²K and 0.1 W/m²K, respectively. This illustrates the need for more cooling when insulating the ground floor. Conversely, in the winter, no significant impact is seen on either the ground or first floor from ground floor insulation. This result confirms that the ground floor should not be insulated.

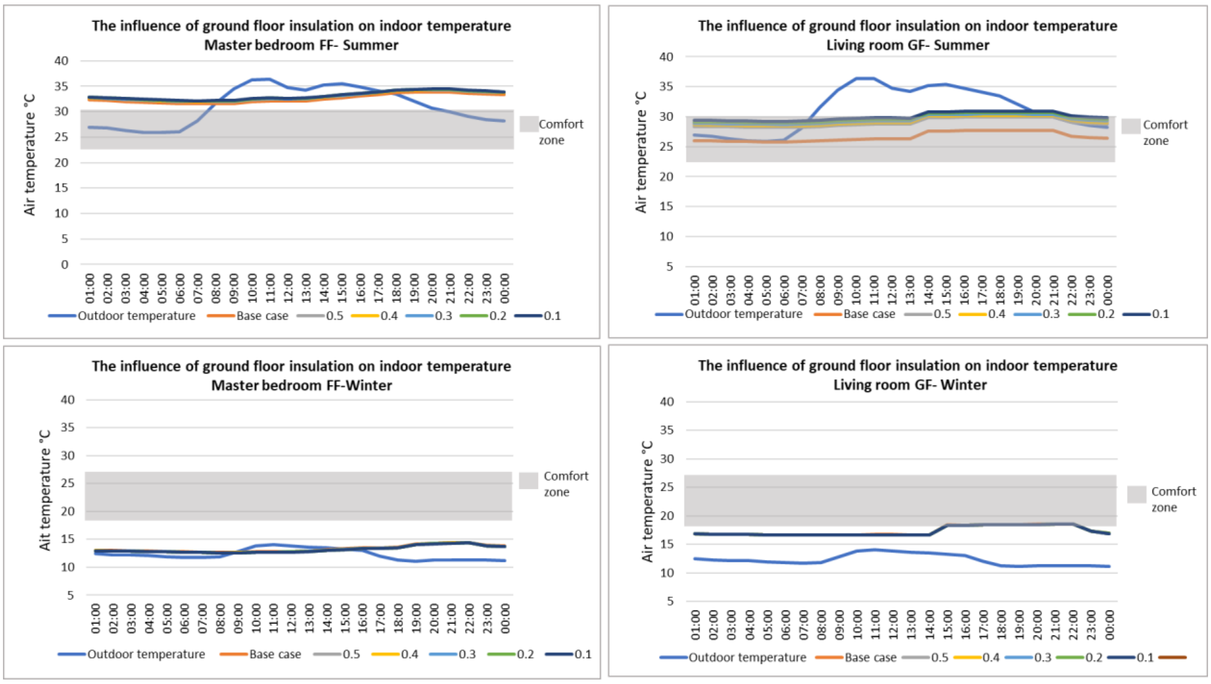


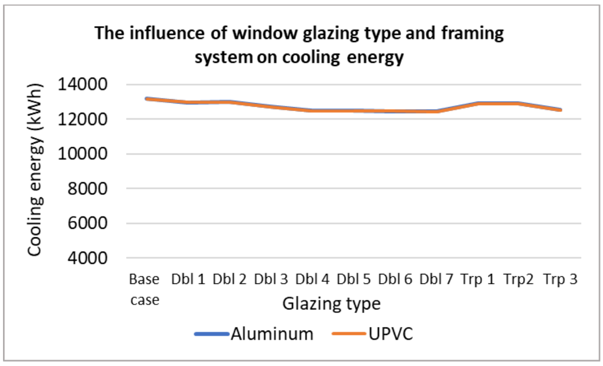
Figure 7. 18 Influence of ground floor insulation on indoor temperature in summer and winter

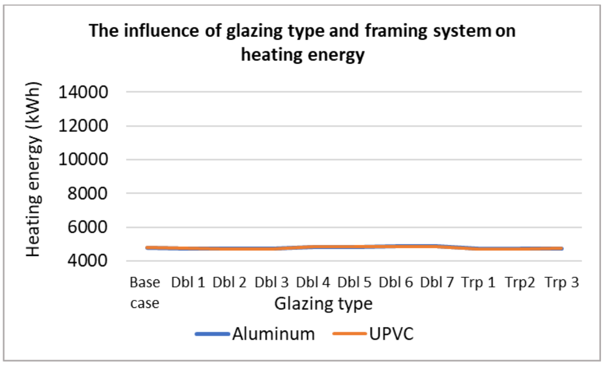
7.3.1.1.4 Window Glazing Type and Framing System

In previous sections, upgrading of the opaque envelope materials by adding insulation is discussed. In this section, the effects of renovating window glazing type and framing system are examined. The base case window glazing type is 6m single clear glass. Ten window glazing types with different thermal and solar characteristics are investigated, including seven types of double glazing and three types of triple glazing with different thermal and solar properties. The wooden frames of the ground floor and the aluminium frames of the first floor are upgraded with a UPVC framing system. In addition, energy-efficient glazing types that affect light transmission are excluded. The solar and thermal properties of the base case glazing type and the energy efficient glazing are described in Table 4.15 in the Methodology Chapter.

Influence of Window Glazing Type on Cooling and Heating Energy Consumption

All of the selected types of glazing reduce cooling energy (Figure 7.19). Neither aluminium framing nor UPVC framing systems show any influence on cooling and heating energy consumption. Moreover, the solar factor has greater influence compared to the U-value of the glazing. Double reflective glazing, which has a lower solar factor and higher U-value than double and triple clear glazing, achieves higher reductions in cooling energy. For instance, reflective double glazing types Dbl 4, Dbl 5, Dbl 6 and Dbl 7, which have the lowest solar factor (LSF) and the highest U-value, produce the highest reductions in cooling energy, of up to 6%. Triple (Trp3) and double (Db3) low emissivity glazing, which have a higher solar factor (MSF) and lower U-value than reflective glazing archives, show less cooling energy reduction, of 5% and 3.5 %, respectively. Double (Db1, Db2) and triple (Trp1, Trp2) clear glazing with the highest solar factor (HSF) show cooling energy reductions of only 1.6% and 2.14%, respectively. In contrast, the reflective glazing types with LSF raise heating energy slightly, by up to 1.2%. This is because the reflective film blocks the solar heat from warming the interior in winter, leading to greater heating energy consumption. Other glazing types produce a minor reduction in heating energy, where only a 1.6% reduction is produced by triple clear glazing (Trp2) and 1% by Triple LoE with argon filling (Trp3). In general, reflective glazing, although slightly increasing the heating energy, reduces the cooling energy more. Triple LoE with argon filling (Trp3) shows good results on both cooling and heating energy reduction, making it the optimal glazing type in reducing the building's energy use. In general, upgrading the window glazing has a low impact on both cooling and heating energy reduction, and this is attributed to the limited solar gain through glazing due to the low window to wall ratio.



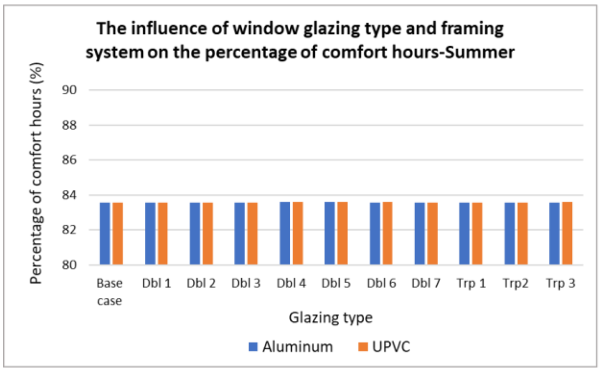


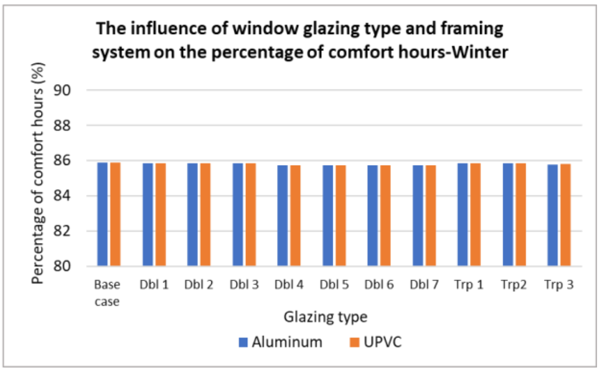
Base case: Sgl Clr 6mm, **Dbl 1**: Dbl Clr 6mm/13mmAir, **Dbl 2**: DblClr/6mm/13mmArg, **Dbl 3**: Dbl LoE Clr 6mm/13mm Arg, **Dbl 4**: Dbl Ref Clr 6mm/13mm Air, **Dbl 5**: Dbl Ref-D Clr 6mm/13mm Arg, **Dbl 6**: Dbl Ref-D Tint 6mm/13mmAir, **Dbl 7**: Dbl Ref-D Tint 6mm/13mm Arg, **Trp 1**: Trp Clr 3mm/13mm Air, **Trp 2**: Trp Clr 3mm/13mm Arg **Trp 3**: Trp LoE Clr 3mm/13mm Arg

Figure 7. 19 Influence of window glazing type and framing system on cooling and heating energy consumption

Influence of Glazing Type and Framing System on Comfort Hours in Summer and Winter.

Figure 7.20 illustrates that upgrading the window glazing with all energy-efficient glazing does not exert a noticeable impact on the percentage of comfort hours experienced during summer or winter and remain within the acceptable limits of ASHRAE 55. This is attributed to the limited solar gain through the window due to the small window to wall ratio.



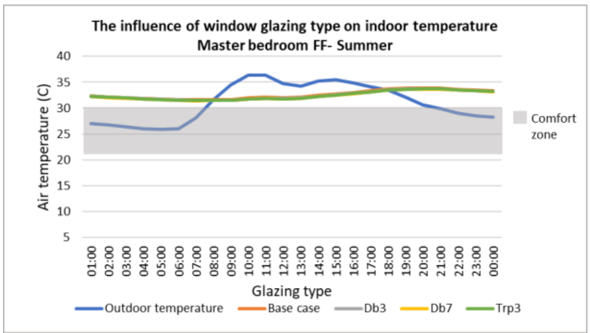


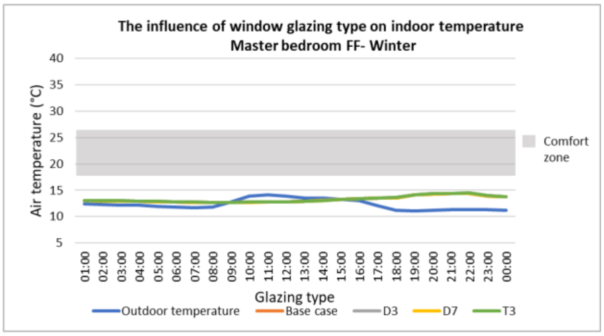
Base case: Sgl Clr 6mm, **Dbl 1**: Dbl Clr 6mm/13mmAir, **Dbl 2**: DblClr/6mm/13mmArg, **Dbl 3**: Dbl LoE Clr 6mm/13mm Arg, **Dbl 4**: Dbl Ref Clr 6mm/13mm Air, **Dbl 5**: Dbl Ref-D Clr 6mm/13mm Arg, **Dbl 6**: Dbl Ref-D Tint 6mm/13mm, **Dbl 7**: Dbl Ref-D Tint 6mm/13mm Arg, **Trp 1**: Trp Clr 3mm/13mm Air, **Trp 2**: Trp Clr 3mm/13mm Arg **Trp 3**: Trp LoE Clr 3mm/13mm Arg.

Figure 7. 20 Window glazing type and frame vs. the percentage of comfort hours in summer and winter

Influence of Window Glazing Type on Indoor Temperature in Summer and Winter

It can be clearly seen in Figure 7.21 that optimising the window glazing with energy efficient glazing types has no influence on indoor temperatures during the summer or winter. This is attributed to the limited solar gain through the window due to the low window to wall ratio.





Base case: Sgl Clr 6mm, **Dbl 3**: Dbl LoE Clr 6mm/13mm Arg, **Dbl 7**: Dbl Ref-D Tint 6mm/13mm Arg, **Trp 3**: Trp LoE Clr 3mm/13mm Arg

Figure 7. 21 Influence of window glazing type on indoor temperature in the summer and winter

7.3.1.1.5 Window Shading

This section investigates the impact of window shading on heating and cooling energy consumption. The case study windows have no shading. To optimise the window with shading, three types of fixed shading device are studied: overhangs, side fins, and surrounding shading (overhangs + side fins) to control solar gain through the windows. The length of horizontal and vertical projection ranges between 0.3m and 1m. Solar shading with more than 1m depth was excluded to avoid issues with appearance and daylighting. Shading specifications can be found in Table 4.16 in the Methodology Chapter.

Influence of Window Shading on Cooling and Heating Energy Consumption

The overall performance of the building changes with the addition of external shading devices depending on the season, as illustrated in Figure 7.22. During the summer, shading devices contribute to cooling energy reductions, in which 4% and 6.5% reductions are achieved by using surrounding shading at 0.5m and 1m projection depths, respectively. However, a reverse effect from these shading devices can be seen in winter, where heating energy witnesses an increase of 3.2% and 4.3% using surrounding shading at 0.5m and 1m projection depth, respectively. Despite this, solar shadings can still be used, as the decrease in cooling energy is much greater than the increase in heating energy.

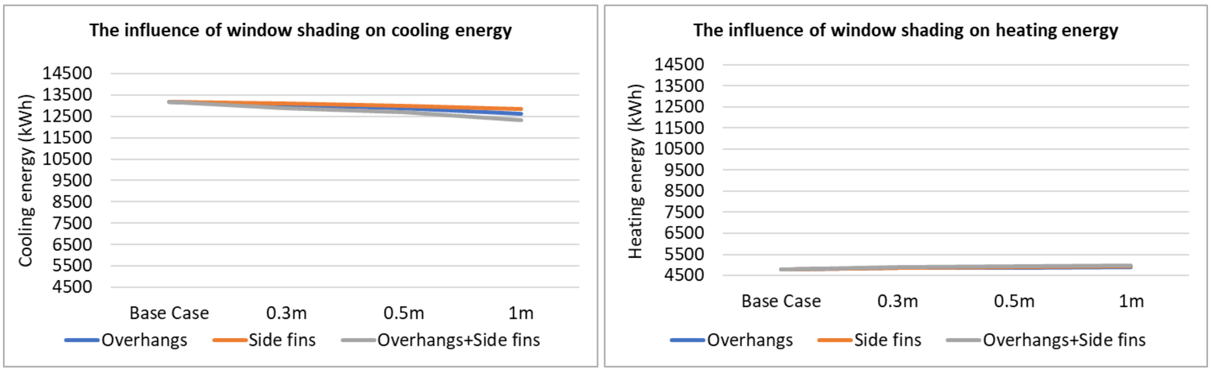


Figure 7. 22 Solar shading devices' influence on cooling and heating energy consumption

Influence of Window Shading Devices on Comfort Hours in Summer and Winter.

Adding solar shading devices to the windows does not affect indoor thermal conditions in the summer season, when the percentage of comfort hours remains stable and within the acceptable limits set by ASHRAE 55. Similarly, in the winter, solar shading has no important impact on the percentage of comfort hours, which remain within the acceptable limits set in ASHRAE 55 (Figure7.23).

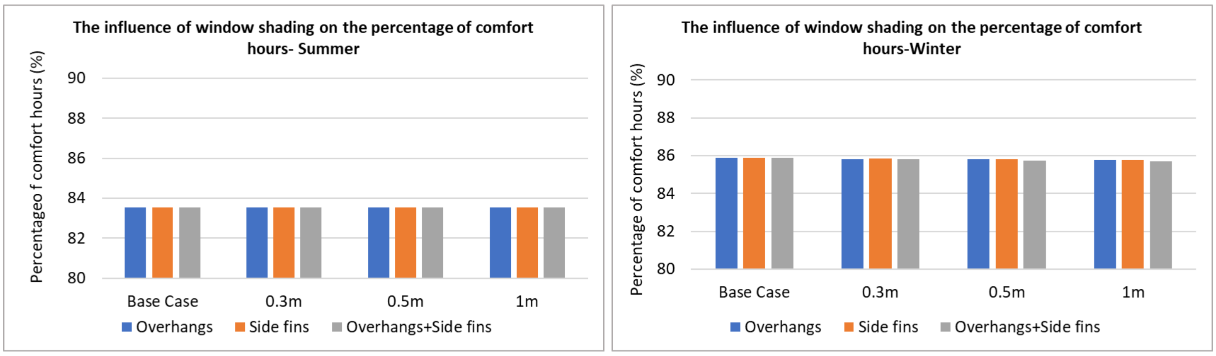


Figure 7. 23 Solar shading devices' influence on the percentage of comfort hours in summer and winter

The Influence of Window Shading on Indoor Temperatures in Summer and Winter

It can be clearly seen in Figure 7.24 that optimising the window with surrounding shading at different projection depths has no influence on indoor temperatures during either the summer or winter. This is attributed to the limited solar gain through the window due to the low window to wall ratio.

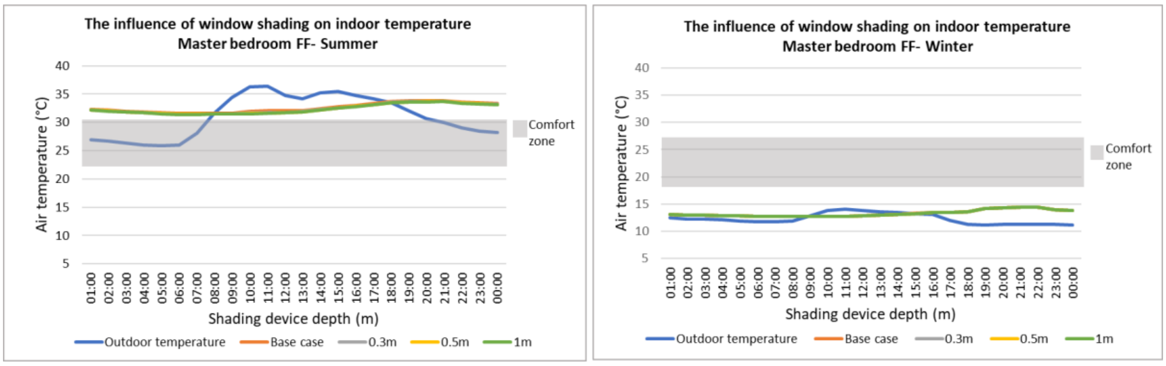


Figure 7. 24 Influence of window shading on indoor temperature in summer and winter

7.3.1.2 Stage 2 Optimisation Results

In this section, the single retrofit measures which have an impact on energy use reduction are combined and used to conduct a multi-objective optimisation where different retrofit measures are combined and assessed using the Pareto optimisation tool in DesignBuilder software. This results in the creation of a number of solutions that achieve a trade-off between energy consumption and percentage of discomfort hours. Moving along the Pareto front curve, all of the optimal trade-off solutions are found. Minimising total site energy consumption and minimising thermal discomfort are determined as the target objectives. The number of options for each parameter is shown in Table 7.1. Two multi-objective optimisation runs were carried out using both high and moderate impact parameters. The first run with external wall and roof insulation, the second run with internal wall and roof insulation. Options details can be found in tables 4.14, 4.15 and 4.16 in the Methodology Chapter.

Table 7. 1 Design parameters options for multi objective optimisation

	Parameters	Number of options
High-impact category	External wall construction GF	20
	External wall construction FF	20
	Roof construction	20
Moderate-impact category	Glazing type	10
	Local shading type	9

It can be observed that a combination of moderate and extreme values of different parameters helps reduce energy demand from 24660.97 kWh/y to 11521 kWh/y. The first simulation includes 1931 iterations, of which the pareto front produces 78 optimal solutions (Figure 7.25). The range of energy consumption for the site across the optimal solutions is 13922.56 kWh/y to 11521.88 kWh/y, and none of the provided optimal solutions compromise on thermal comfort. The second simulation includes 1934 iterations, of which the pareto front produces 76 optimal solutions (Figure 7.26). The range of energy consumption for the site across optimal solutions is 14022.55 kWh/y to 11608.13 kWh/y. Accordingly, the position of the insulation material, whether internal or external, does not have a substantial impact on energy use reduction.

Optimal retrofit solutions

The most optimal design solution, producing the lowest site energy consumption, with an acceptable range of 85 % annual comfort hours at 53.27% energy reduction, includes the following design parameters:

- Roof with external insulation with a U-value of 0.1 W/m²K,
- Walls with external insulation with a U-value of 0.1 W/m²K,
- 'Trp LoE Clr 3mm/13mm Arg' glazing with a U-value of 0.78 W/m²K and SHGC of 0.47.
- Side fins of 0.5m +0.5 overhang for shading the NE windows, a 0.5m projection Louvre+30° for shading the SE windows, side fins of 0.5m +0.5 overhang for shading the SW windows, and side fins of 0.3m +0.3 overhang for shading the NW windows

The optimal simulation which improves indoor thermal comfort to 87% annual comfort hours at 43.54% energy reduction includes the following design parameters,

- Roof with internal insulation with a U-value of 0.2 W/m² K,

- Walls with external insulation with a U-value of 0.4 W/m²K for first floor walls, and with a U-value of 0.3 W/m²K for the ground floor walls.
- 'Trp Clr 3mm/13mm Arg' glazing with a U-value of 1.6W/m²K and SHGC of 0.68.
- 0.5m overhangs for shading NE and SW windows, side fins of 0.3 for shading the SE windows, and a 0.5m overhang for shading the NW windows.

The primary energy consumption of the base case model is reduced from 209 kWh/m²/y to 124 kWh/m²/y, meeting the Passivhaus retrofit target of 135 kWh/m²/y. The primary cooling and heating energy demand is reduced from 124.21 kWh/m²/y to 40.76 kWh/m²/y.

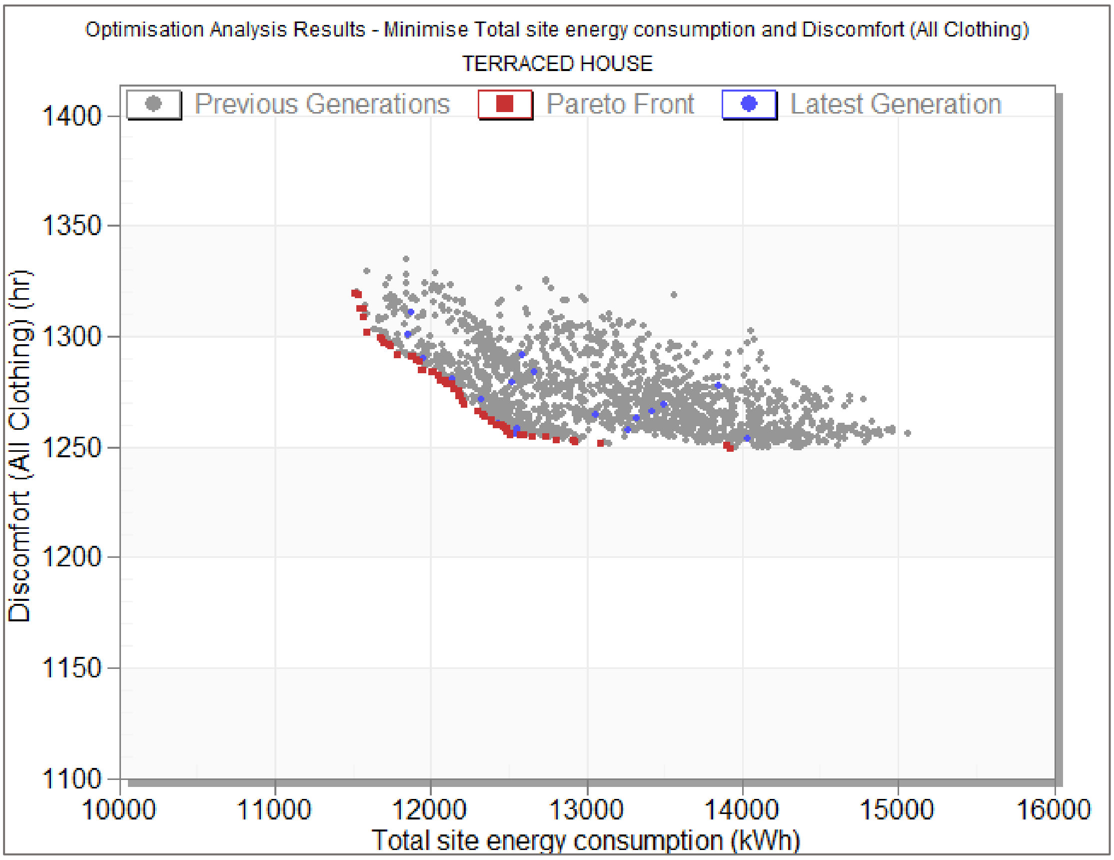


Figure 7. 25 Multi - objective optimisation results 1,- Case Study 1.

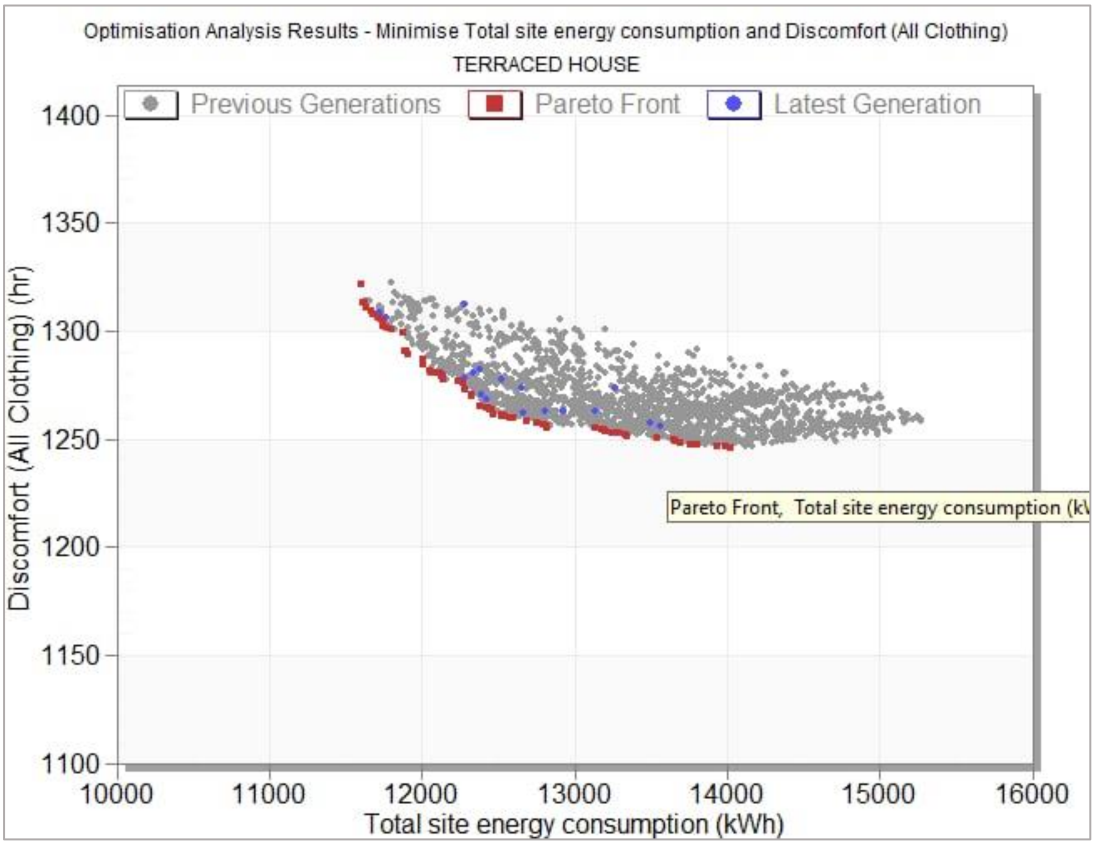


Figure 7. 26 Multi - objective optimisation results 2, Case study 1.

Influence of the Optimal Retrofit Solution on Indoor Temperature - Case Study 1

This section studies the influence of the optimal solution on the indoor temperature of the building in Case Study 1 during summer and winter. The optimal solution that is described in the previous section Includes an upgraded roof and wall with biobased insulation at a U-value of 0.1 W/m^{2}K, which may be difficult to apply in practical terms because it requires thick insulation material, ranging between 0.36m and 0.48m. This thickness requires sufficient space for its application, whether inside or outside the building. Therefore, a second simulation run was conducted to investigate the effect of the optimal solution on indoor temperature but with the roof and wall U-value at 0.5 W/m^2 K, which requires a lower insulation thickness of between 0.061m and 0.079m.

As illustrated in Figure 7.27, the simulation results for the summer show that the optimal solution can achieve a remarkable reduction in indoor temperature. This reduction is between 4.5 °C and 6.5°C in the master bedroom on the first floor at wall and roof U-values of 0.5 W/m^2 K and 0.1 W/m^2 K, respectively, and brings the indoor temperature to a comfortable level. Similarly, in winter, a noticeable increase in indoor temperature is witnessed. For instance, the temperature in the master bedroom is raised by 3°C at a wall and roof U-value of 0.5 W/m^2 K. The temperature is increased further, by 5°C, through the optimal solution with a roof and wall U-value of 0.1 W/m²K. However, despite this increase in indoor temperature in the winter, electrical heating is still needed to bring indoor temperatures to a comfortable level on the first floor.

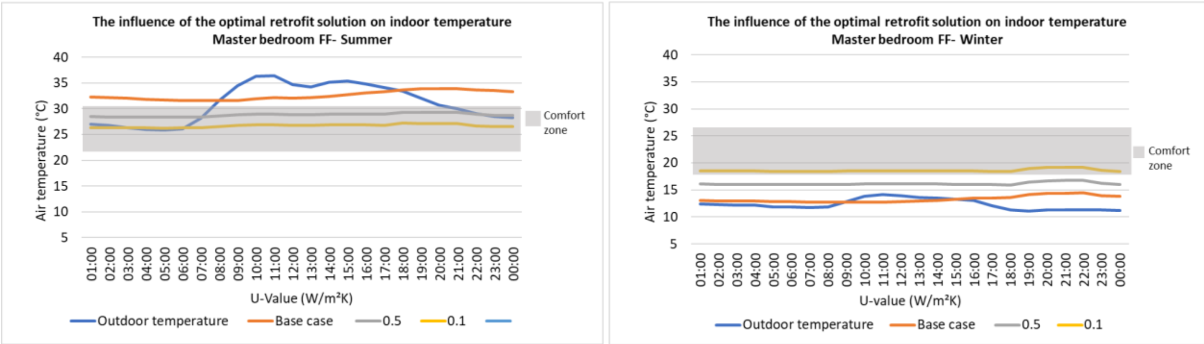


Figure 7. 27 Influence of the optimal retrofit solution on indoor temperature in summer and winter

7.3.1.2.1 Further optimisation scenarios

- **Further energy reductions from adjusting the cooling and heating setpoints based on the acceptable comfort ranges of ASHRAE Standard 55**

According to ASHRAE 55 standards, indoor thermal comfort levels in Libya range from 22°C to 30°C in the summer, and from 19°C-26°C in the winter. This means that people can feel comfortable at 26 °C in the summer and at 22°C in the winter. However, based on the building survey, the cooling set point is set at 22°C on the first floor and at 24 °C on the ground floor. In the winter, the heating set point is set at 24°C on the ground floor, and on the first floor, it is set at 29°C, 27°C, and 25 °C, respectively in the kids' room, the lounge and the reception, which is higher than what is needed to provide the occupant with comfort. Accordingly, if the set points of the base case model are adjusted based on acceptable comfort ranges for summer and winter, further energy reductions can be achieved.

To investigate this, the optimised Case Study 1 is further optimised by adjusting the cooling set point to 26 °C and the heating set point to 22 °C. The simulation results show that adjusting the cooling and heating set points in the optimised model achieves a 14.73% additional site energy reduction. The primary energy is reduced more to 95.88 kWh/m²/y, and the primary cooling and heating energy is reduced further to only 11.96 kWh/m²/y, meeting the Passivhaus target for retrofits.

- **Optimisation of Base Case Study 1 with roof and wall insulation only**

A passive retrofit solution which only incorporates roof and wall insulation achieves a 34.3% site energy reduction at a roof and wall U-value of 0.5 W/m² K. Primary energy is reduced from 209 kWh/m²/y to 148.26 kWh/m²/y, while cooling and heating energy is reduced from 124.21 kWh/m²/y to 62.7 kWh/m²/y. At a roof and wall U-value of 0.1, greater energy reduction is achieved. Site energy consumption is reduced by 45.9%, and primary energy is reduced from 209 kWh/m²/y to 133.70

kWh/m²/y, while cooling and heating energy is reduced from 124.21 kWh/m²/y to 49.78 kWh/m²/y. However, the Passivhaus target for retrofits cannot be reached with this solution.

- **Optimisation of the Base Case Study 1 Model as a Fully Conditioned Building**

When optimising the base case model as a fully conditioned building through the optimal retrofit solution, it is found that primary energy consumption is reduced from 406.4 kWh/m²/y to 176.30 kWh/m²/y. The primary cooling and heating energy demand is reduced from 315.4 kWh/m²/y to 64.62 kWh/m²/y. By adjusting the cooling and heating set points based on the acceptable comfort range in Libya, additional energy reductions are achieved. The cooling set point is adjusted to 26 °C, and the heating set point is adjusted to 22 °C. The simulation results show that optimising the set points can achieve further energy reductions, in which primary energy demand is reduced to 113.21 kWh/m²/y, and cooling and heating energy demand is reduced to 26.6 kWh/m²/y, meeting the Passivhaus retrofit target.

7.3.1.3 Stage 3 Optimisation Results

As mentioned in Section 7.3.1.1 thermally renovating the building envelope could contribute to a 53.27% reduction in the site energy consumption. To meet the remaining 46.73% of energy needs and achieve the target for NZEBs, a PV system of 400W is installed on the roof. The simulation results show that a solar PV system consisting of 16 solar panels of 400W arranged in two parallel lines with a total area of 32 m^2 meets the remaining energy needs and achieves NZEBs targets. Moreover, there remains sufficient space on the roof for an additional 16 panels, to supply the energy requirements of an additional two storeys. Figure 7.28 shows locations and areas for the installation of photovoltaic panels on the roof of case study 1. Table 7.2 shows a range of solutions, including the optimal solutions, the resultant energy savings, and the number of solar panels required to achieve the zero-energy buildings target with each solution.

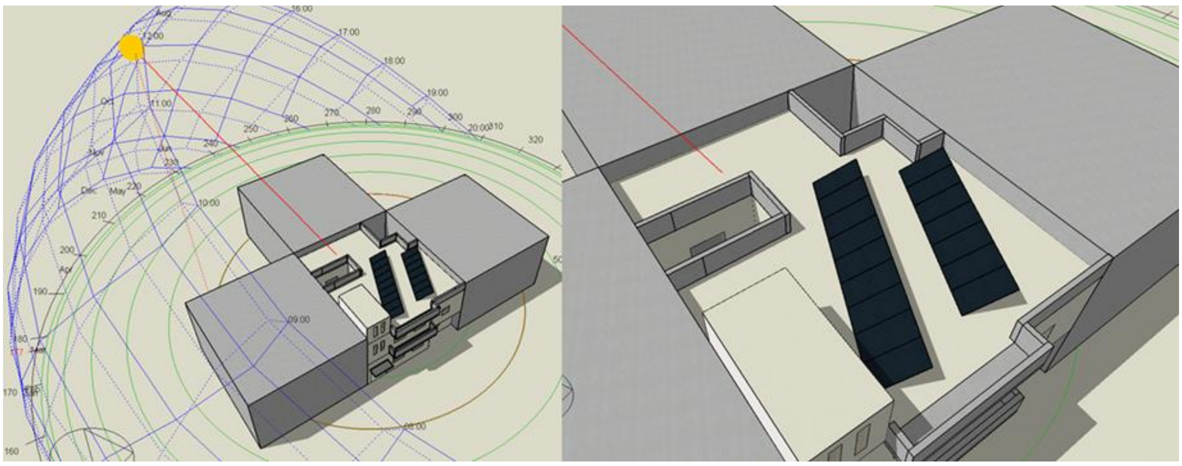


Figure 7. 28 Photovoltaic panel arrangement- Case Study 1

Table 7. 2 The optimal retrofit solutions and number of solar panels needed to meet NZEBs- Case Study1

	Site energy consumption (kWh)	Percentage of comfort Hours (%)	Primary energy demand (kWh/m²/y)	Primary cooling and heating Energy (kWh/m²/y)	U-Value (W/m²k) FF wall; GF wall; Roof	Saving (%)	Remaining energy need (%)	No of Panels to NZEB
The optimal solution	11521.88	84.73	124	40.26	0.1; 0.1; 0.1	53.27	46.73	16
The optimal solution with different wall and roof U-values	12653.76	85.48	129.49	44.52	0.2; 0.2; 0.2	48.69	51.31	17
	13653.23	85.52	133.65	48.35	0.3; 0.3; 0.3	44.63	55.36	19
	14336.1	85.65	137.78	52.31	0.4; 0.4; 0.4	41.87	58.13	19
	15065.61	85.69	141.60	56.03	0.5; 0.5; 0.5	39%	61%	20
The optimal solution + adjustment of cooling and heating set points	7816.04	83.51	95.88	11.96	0.1; 0.1; 0.1	68%	32%	11
	9930.59	83.20	109.35	23.78	0.5; 0.5; 0.5	59.7%	40.27	14
Roof and wall insulation only	13324.40	85.18	133.70	49.78	0.1; 0.1; 0.1	45.9%	54.1	18
	16195.61	85.45	148.26	62.7	0.5; 0.5; 0.5	34.3%	65.7	22

7.3.2 Case Study 2- Optimisation Results

7.3.2.1 Stage 1 Optimisation Results

7.3.2.1.1 Roof Insulation

This section examines the impact of upgrading the base case roof with biobased insulation materials. The existing roof of Case Study 2 has a U-value of 2.05 W/m²K. The U-values selected for optimising the roof range between 0.5 W/m²K and 0.1 W/m²K in decrements of 0.1. The analysis also considers the effect of the insulating materials' position, both inside and outside. The specifications of the optimised roof with insulation materials at different thicknesses are described in Table 4.14 in the Methodology Chapter.

Influence of Roof Insulation on Cooling and Heating Energy

The influence of roof insulation on cooling and heating energy is shown in Figure 7.29. Reducing the base case U-value of the roof to 0.5 W/m²K by adding insulation materials internally reduces cooling and heating energy by 27.9% and 25.9%, respectively. As the U-value drops to 0.1 W/m²K, cooling and heating decrease much further, reaching 35.6% and 33.1%, respectively. External insulation has a similar influence on cooling and heating energy, in which reducing the roof U-value to 0.5 W/m²K reduces cooling energy by 29.3% and heating energy by 25.3%. The cooling and heating energy decrease further, to 35.6% and 33.6%, respectively, at a roof U-value of 0.1 W/m²K. Accordingly, energy savings are not significantly affected by the location of insulation materials. The variation between insulation materials in terms of energy reduction is minor and cannot be seen in the figure, as the four insulating materials achieve relatively similar percentage reductions in cooling and heating energy. This is because the insulation materials have similar thermal properties.

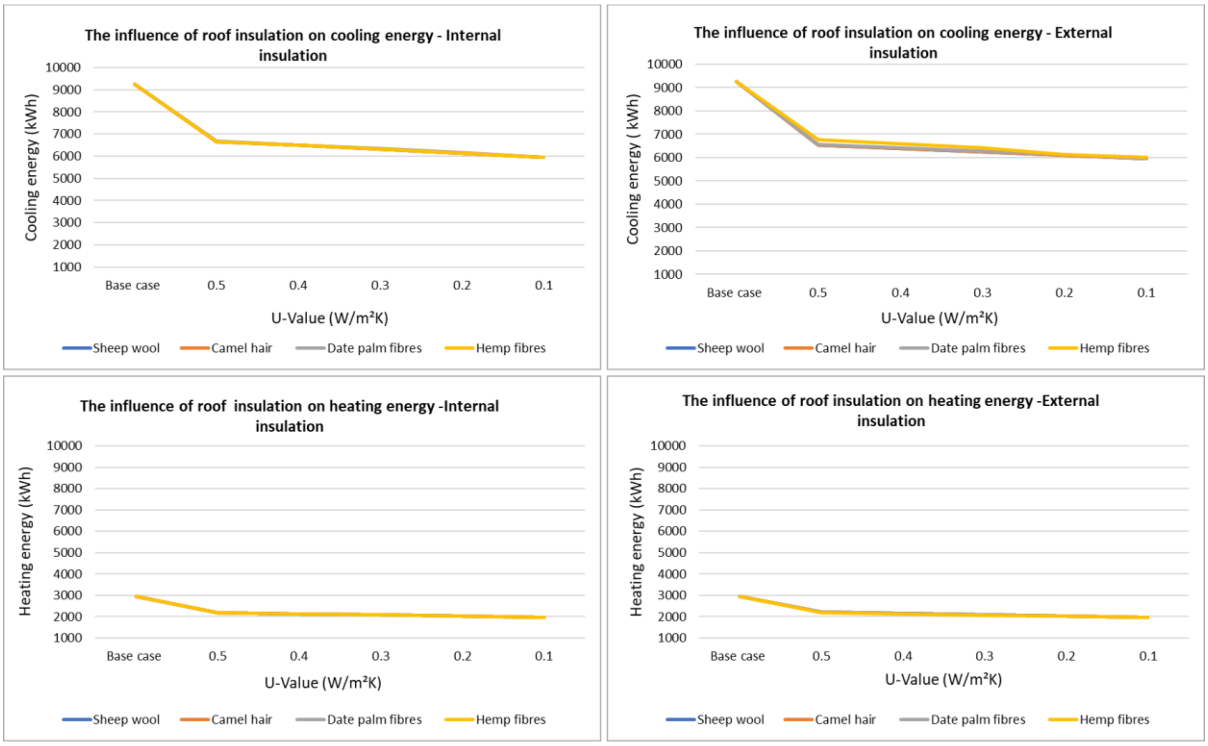


Figure 7. 29 The effect of roof insulation on cooling and heating energy consumption

Influence of Roof Insulation on The Comfort Hours in Summer and Winter

Figure 7.30 demonstrates that the insulation material, whether applied internally or externally, marginally improves the percentage of comfort hours for indoor spaces during the summer, with an increase of about 1% achieved during this season. Similarly, in winter, insulating the roof leads to an increase in the percentage of comfort hours of up to 2%.

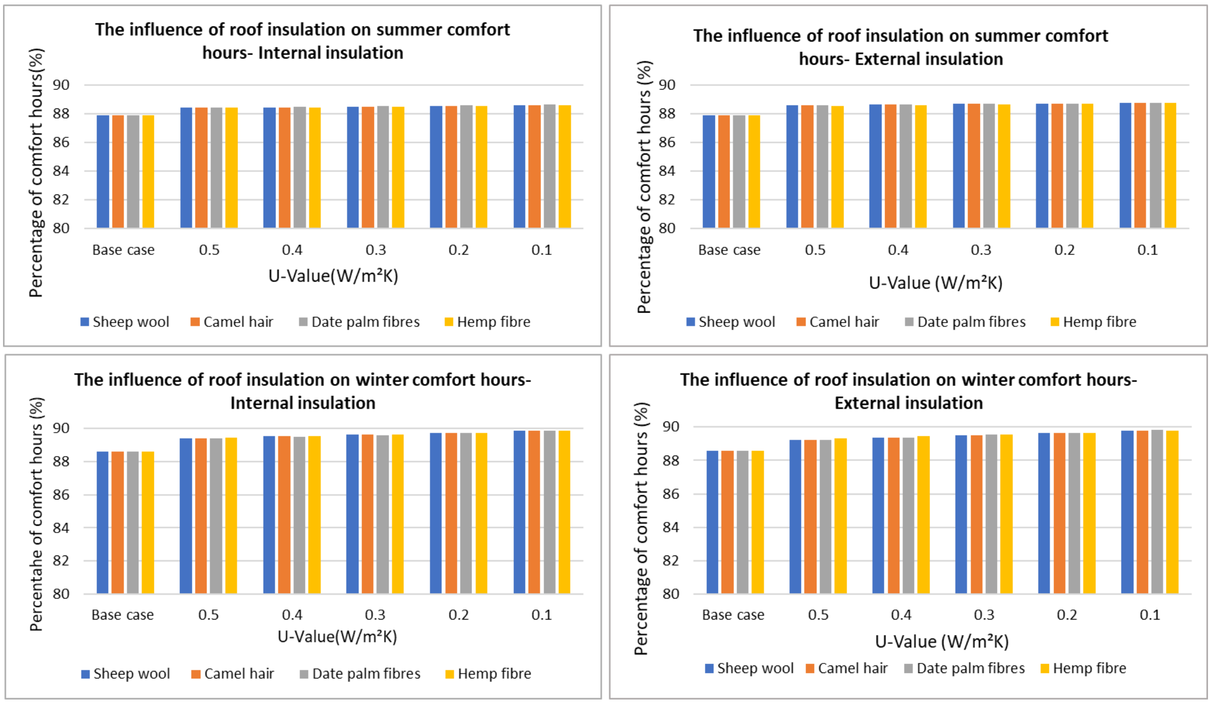


Figure 7. 30 Influence of roof insulation on the percentage of comfort hours during summer and winter

Influence of Roof Insulation on Indoor Temperature in Summer and Winter

Figure 7.31 shows that roof insulation with biobased material affects the indoor temperature of the unconditioned spaces in summer and winter. In summer, bedroom 1 witnesses a decrease in indoor temperature of 1.5 °C and 2.5 °C at roof U-values of 0.5 W/m²K and 0.1 W/m²K, respectively, making the indoor temperature more comfortable. Similarly, in winter, an increase of up to 1.7°C in indoor temperature is achieved when reducing the roof U-value to 0.1 W/m²K. Despite this increase in temperature, however, the temperature is still below a comfortable level.

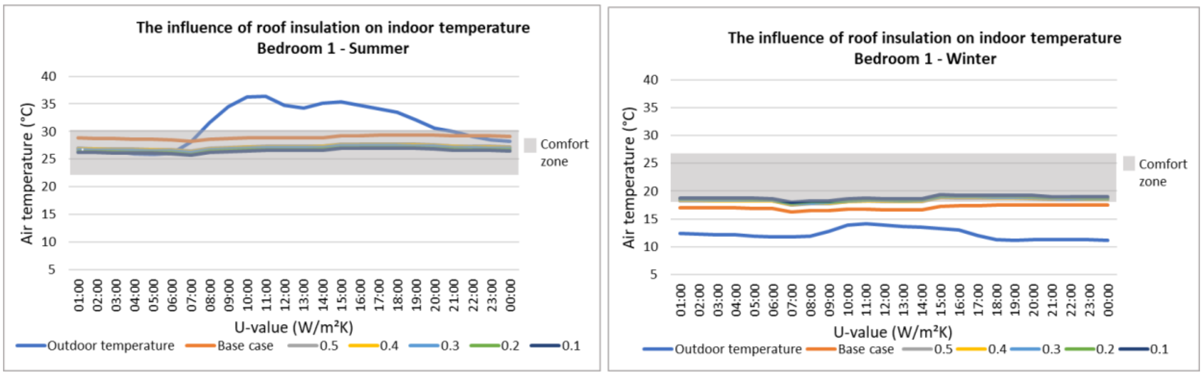


Figure 7. 31 Influence of roof insulation on indoor temperature in summer and winter

7.3.2.1.2 External Wall Insulation

This section examines the impact of upgrading the walls with biobased insulation materials. The base case walls of Case Study 2 have a U-value of 2.61 W/m²K. The U-values selected for optimising the building walls range between 0.5 W/m²K and 0.1 W/m²K in decrements of 0.1. The specifications of the walls optimised with insulation materials at different thicknesses are described in Table 4.14 in the Methodology Chapter.

Influence of External Wall Insulation on Cooling and Heating Energy Consumption

Figure 7.32 illustrates the effect of wall insulation on cooling and heating energy. When adding the insulation materials internally, cooling energy is reduced by 34.8% and heating energy is reduced by 25.6% at a wall U-value of 0.5 W/m²K. When the U-value is reduced further to 0.1 W/m²K, cooling and heating energy drop further, by 44.84% and 29.15%, respectively. Similarly, external application of wall insulation reduces cooling and heating energy by 33.9% and 25.6 %, respectively at a wall U-value of 0.5 W/m²K. Cooling and heating energy is decreased further by 43.7%, and 28.8 % respectively at a wall U-value of 0.1 W/m²K. Hence, implementing wall insulation is effective in reducing energy regardless of whether it is applied internally or externally. The four insulating materials reduce cooling and heating energy by percentages that are comparatively close to each other due to the similarity of their thermal properties.

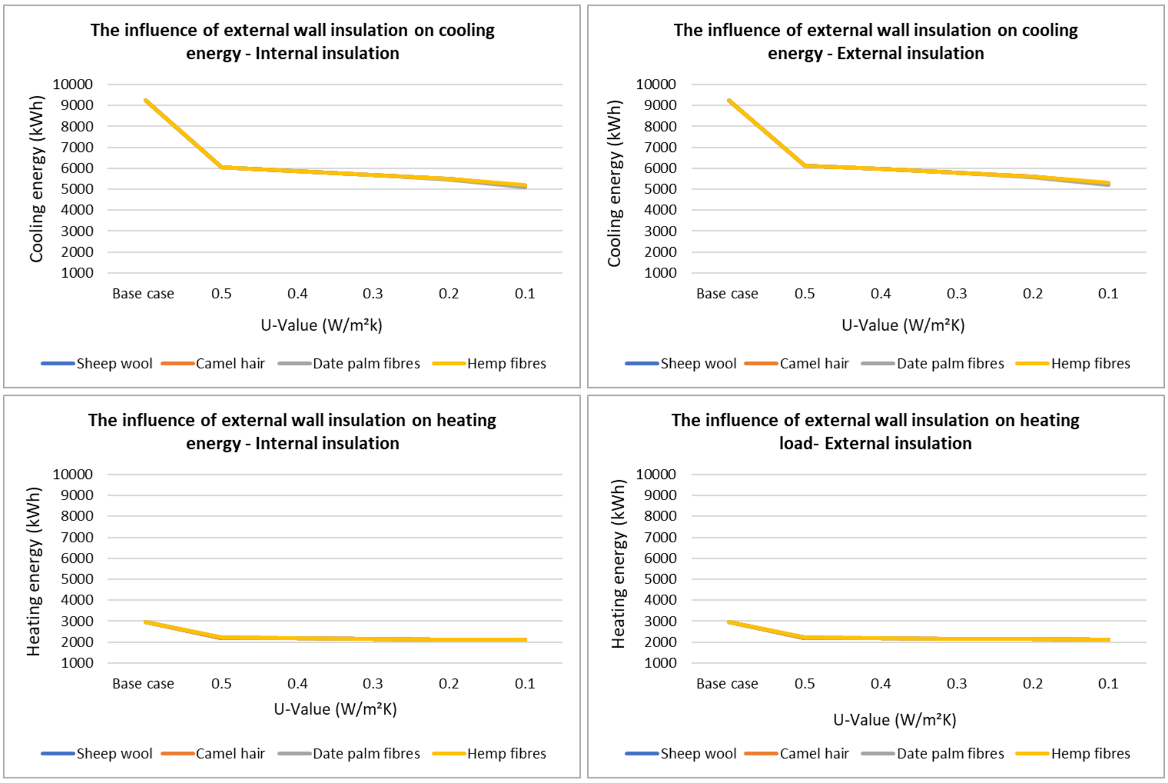


Figure 7. 32 Influence of external wall insulation on cooling and heating energy consumption

Influence of External Wall Insulation on Comfort Hours in Summer and Winter.

In terms of indoor thermal conditions during summer and winter, an up to 1.5 % drop in the percentage of comfort hours is witnessed during the winter, regardless of whether wall insulation is added internally or externally. However, the percentage of comfort hours remains within the comfort limits of ASHRAE Standard 55. Conversely, in summer, whether insulation is added internally or externally, the percentage of comfort hours increases by only 1% (Figure 7.33).

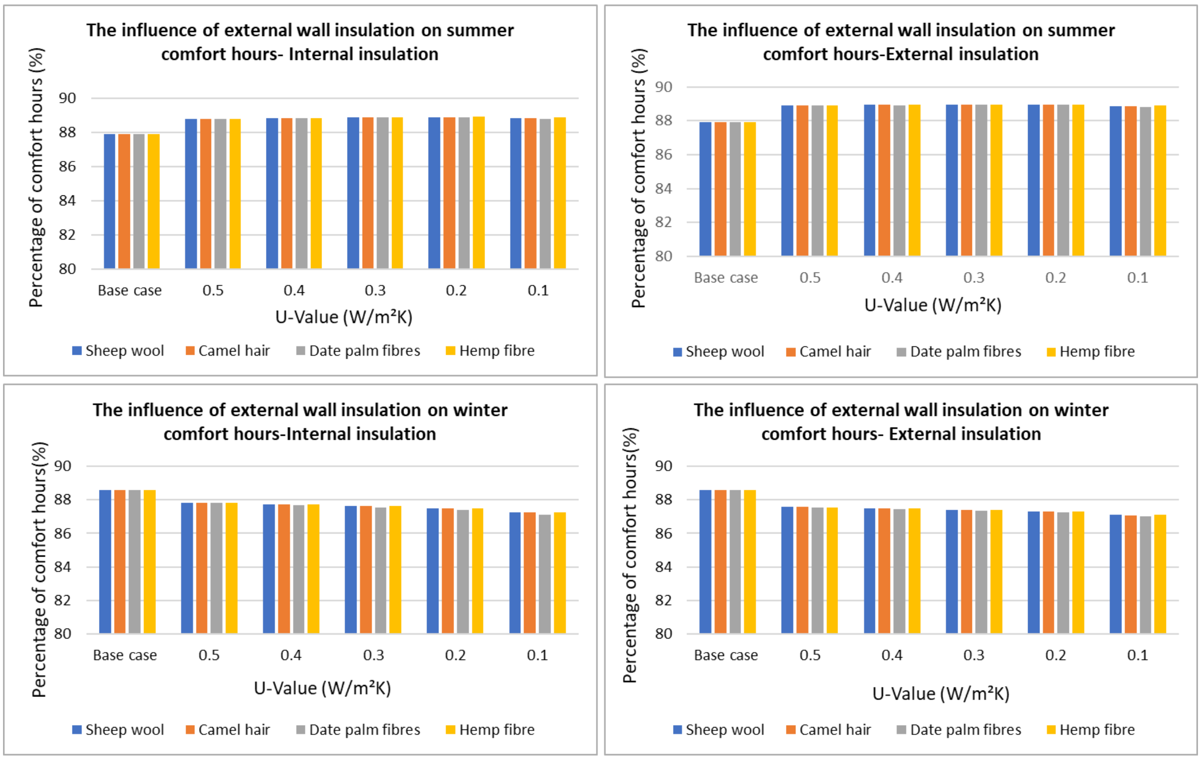


Figure 7. 33 Influence of external wall insulation on the percentage of comfort hours during summer and winter

Influence of External Wall Insulation on Indoor Temperature in Summer and Winter

As illustrated in Figure 7.34, insulating the external walls creates no change in the indoor temperature of bedroom 1 during winter. However, in summer, a decrease in indoor temperature is seen of 1.1 °C at a wall U-value of 0.5 W/m²K, and of 1.3°C at a wall U-value of 0.1 W/m²K, making the indoor temperature more comfortable.

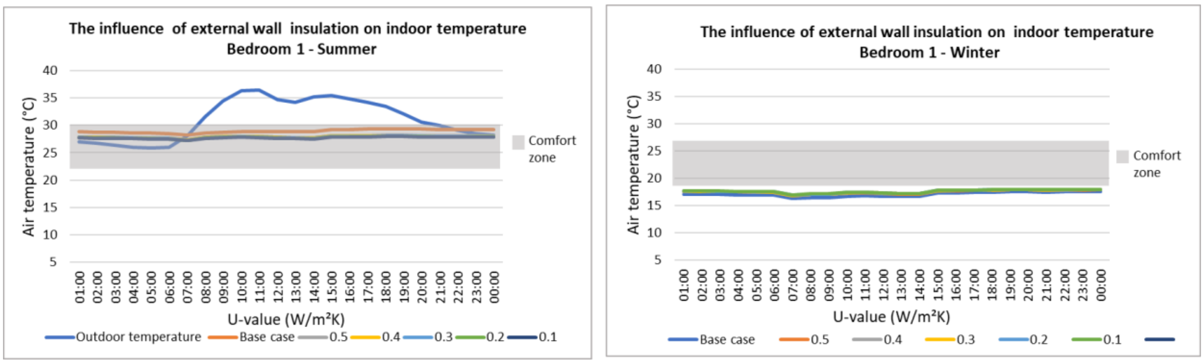


Figure 7. 34 The influence of external wall insulation on indoor temperature in summer and winter

7.3.2.1.3 Ground Floor Insulation

This section involves an investigation of the influence of insulation materials when applied to the internal surface of the ground floor. The base case ground floor has a U-value of 1.5 W/m²K. The U-values selected for optimising the internal surface of the ground floor range between 0.5 W/m²K and 0.1 W/m²K, in decrements of 0.1. The specifications of the optimised ground floor slab with insulation materials at different thicknesses are described in Table 4.14 in the Methodology Chapter.

Influence of Ground Floor Insulation on Cooling and Heating Energy

Ground floor insulation, as shown in Figure 7.35, contributes to an increase in cooling energy in which an approximately 29.5% increase is witnessed at a floor U-value of 0.5 W/m²K. The increase in cooling energy continues to up to 44.9% with the decreases in floor U-value to 0.1 W/m²K. In contrast, heating energy experiences a 4.6% decrease at a floor U-value of 0.5 W/m²K. As the U-value decreases to 0.1 W/m²K, the heating energy is decreased by up to 6.2%. However, because the increase in cooling energy is far greater than the decrease in heating energy, it is not recommended to insulate the ground floor, but rather to keep it uninsulated to utilise the thermal mass of the floor and help reduce cooling energy in the summer. Therefore, ground floor insulation is exempt from the multi-objective optimisation stage.

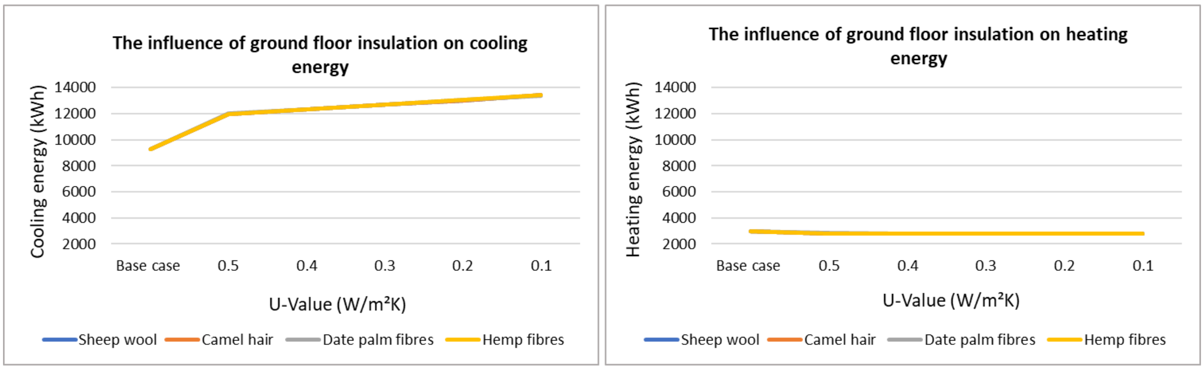
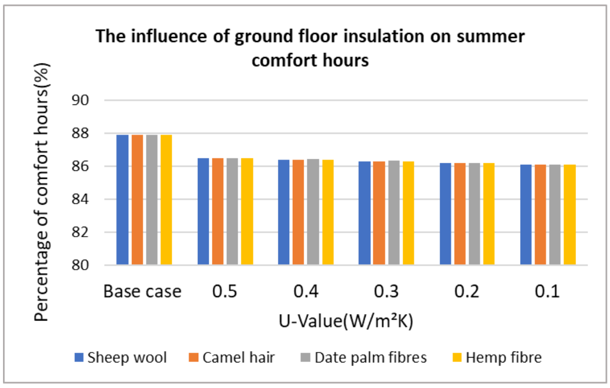


Figure 7. 35 Influence of ground floor insulation on cooling and heating energy

Influence of ground floor insulation on comfort hours in summer and winter.

Regarding indoor thermal conditions, there is a drop in the percentage of comfort hours in the summer, and the percentage of comfort hours is reduced by 2% at a floor U value of 0.1W/m^{2}k. On the other hand, there is only a 0.5% increase in comfort hours with increase in floor U-value in winter (Figure 7.36).



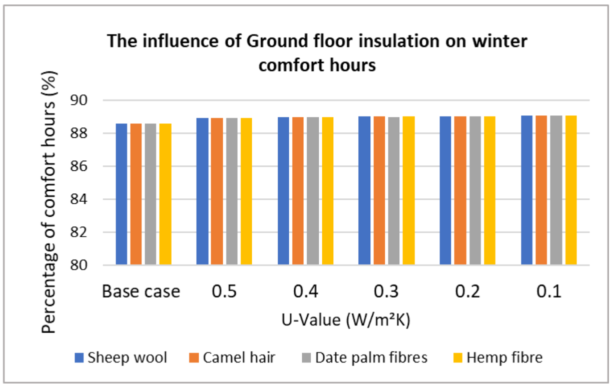
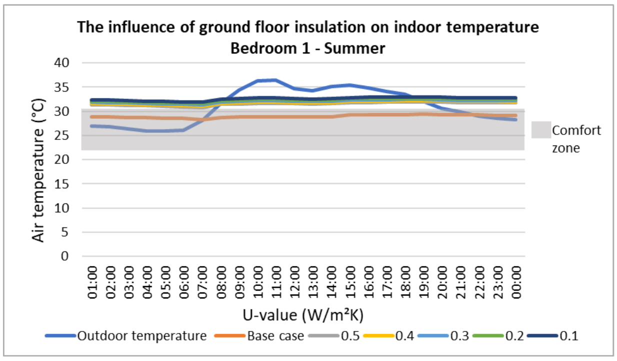


Figure 7. 36 Influence of ground floor insulation on the percentage of comfort hours during summer and winter

Influence of Ground Floor Insulation on Indoor Temperature in the Summer and Winter

Insulating the ground floor has a noticeable impact on indoor temperature during summer only (Figure 7.37). The indoor temperature of bedroom 1, for instance, witnesses increase of about 2.7° C and 3.7° C at floor U-values of 0.5 W/m²K and 0.1 W/m²K, respectively. This illustrates the need for more cooling when insulating the ground floor. Conversely, in the winter, no impact is seen from insulating the ground floor. This result confirms that the ground floor should not be insulated.



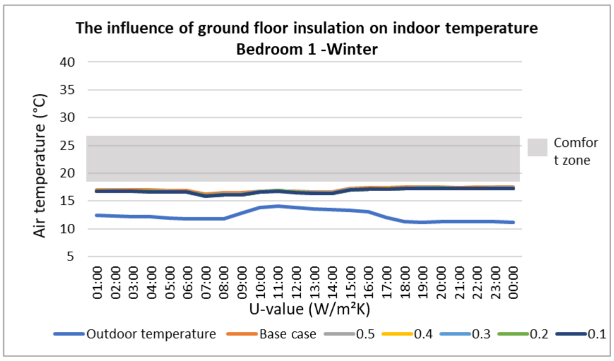


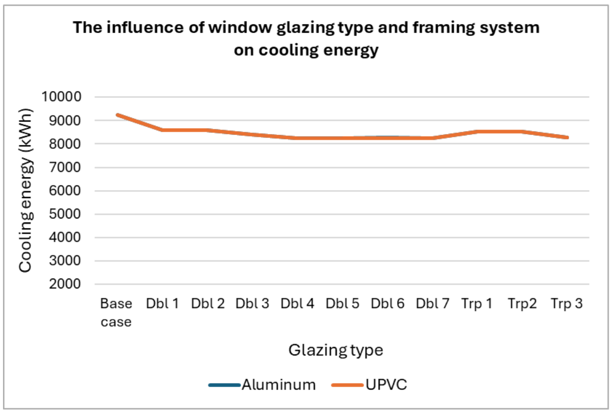
Figure 7. 37 Influence of ground floor insulation on indoor temperature in the summer and winter

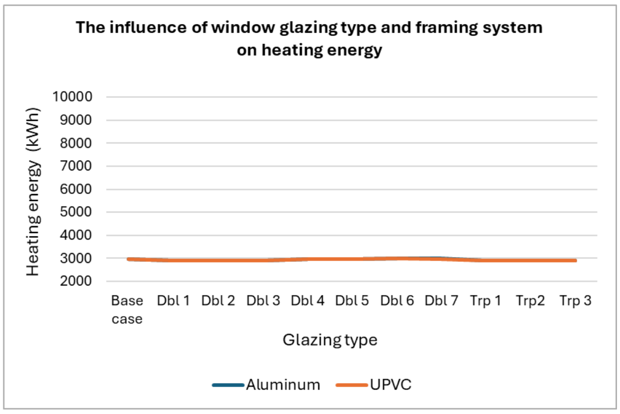
7.3.2.1.4 Window Glazing Type and Framing System

In this section, the effects of upgrading the window glazing type and framing system are examined. The base case window glazing type is 6m single clear glass with aluminium framing, and this is upgraded using seven types of double glazing and three types of triple glazing with different thermal and solar characteristics and UPVC framing systems. Energy-efficient glazing types that affect light transmission are excluded. The solar and thermal properties of the existing glazing type and of the glazing types used for optimising the windows are described in Table 4.15 in the Methodology Chapter.

Influence of Window Glazing Type on Cooling and Heating Energy Consumption

All of the selected types of glazing reduce cooling energy (Figure 7.38). Aluminium framing and UPVC framing systems show the same influence on cooling and heating energy. In addition, the solar factor has a stronger influence compared to the U-value of the glazing. Double reflective glazing, which has a lower solar factor and higher U-value than double and triple clear glazing, achieves a higher reduction in cooling energy. For instance, reflective double glazing (Dbl 4, Dbl 5, Dbl 6, Dbl 7) with the lowest solar factor (LSF) and the highest U-value produces the highest reduction in cooling energy, of up to 10.9 %. Triple (Trp3) and double (Db3) low emissivity glazing, with a higher solar factor (MSF) and lower U-value than reflective glazing, achieve cooling energy reductions of 10.5 % and 9.2 %, respectively. Double (Db1, Db2) and triple (Trp1, Trp2) clear glazing with the highest solar factor (HSF) show cooling energy reductions of 7.2% and 8%, respectively. In contrast, reflective glazing with a low solar factor (LSF) raises heating energy slightly: by up to 0.7%. This is because the reflective film blocks the solar heat from warming the interior in winter, leading to greater heating energy consumption. Other glazing types produce a minor reduction in heating energy: only a 2.4% reduction is produced by triple clear glazing (Trp2) and a 1% reduction is achieved using Triple LoE with argon filling (Tpr3). In general, reflective glazing, although slightly increasing heating energy, reduces cooling energy by a larger amount. Both triple LoE with argon filling (Tpr3), and triple clear glazing with argon filling (Trp2) show good results for both cooling and heating energy reduction, making these glazing types optimal for reducing the building's energy consumption.





Base case: Sgl Clr 6mm, **Dbl 1**: Dbl Clr 6mm/13mmAir, **Dbl 2**: DblClr/6mm/13mmArg, **Dbl 3**: Dbl LoE Clr 6mm/13mm Arg, **Dbl 4**: Dbl Ref Clr 6mm/13mm Air, **Dbl 5**: Dbl Ref-D Clr 6mm/13mm Arg, **Dbl 6**: Dbl Ref-D Tint 6mm/13mmAir, **Dbl 7**: Dbl Ref-D Tint 6mm/13mm Arg, **Trp 1**: Trp Clr 3mm/13mm Air, **Trp 2**: Trp Clr 3mm/13mm Arg **Trp 3**: Trp LoE Clr 3mm/13mm Arg

Figure 7. 38 Influence of window glazing type and framing system on cooling and heating energy consumption

Influence of Glazing Type and Framing System on The Comfort Hours in Summer and Winter

Figure 7.39 shows that optimising the window glazing type does not give a noticeable impact on the percentage of comfort hours during summer and winter, which remain stable within the acceptable limits set in ASHRAE 55.

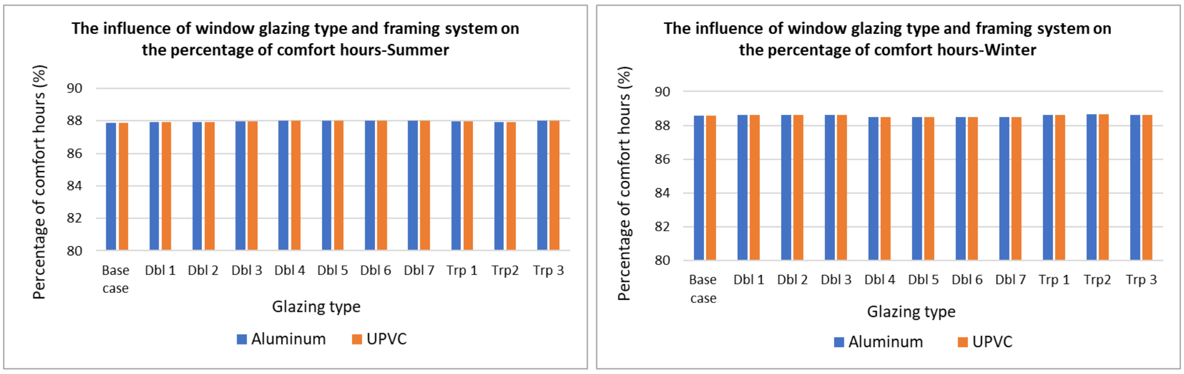


Figure 7. 39 Influence of window glazing type and framing system on the percentage of comfort hours during summer and winter

Influence of Window Glazing Type on Indoor Temperature in Summer and Winter

It can clearly be seen in Figure 7.40 that optimising the window glazing with energy efficient glazing types has no influence on indoor temperatures during the summer or winter. This is attributed the limited solar gain through the window due to the low window to wall ratio.

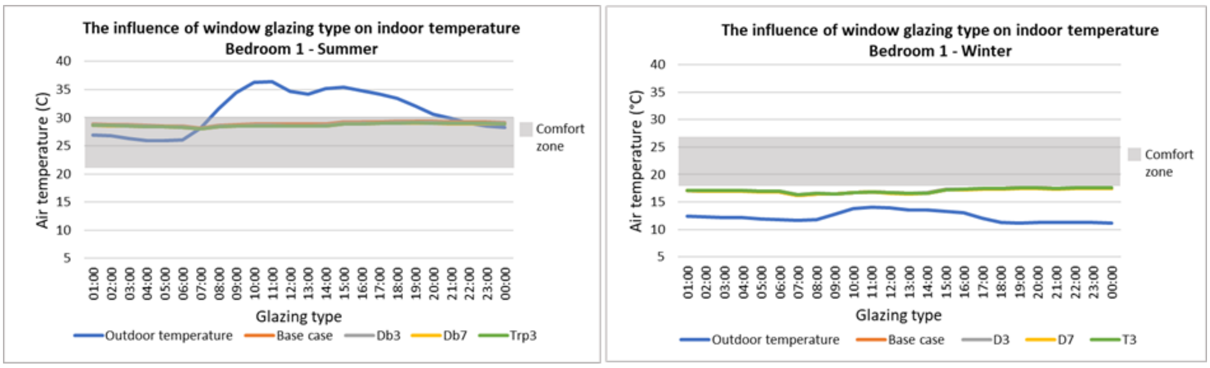


Figure 7. 40 Influence of window glazing type on indoor temperature in summer and winter

7.3.2.1.5 Window Shading

This section investigates the impact of window shading on heating and cooling energy. The base case windows have no shading. In order to optimise the window with shading, three types of fixed shading devices are studied: overhangs, side fins, and surrounding shading (overhangs + side fins) to control solar gain through the windows. The length of horizontal and vertical projection ranges between 0.3m and 1m. Solar shading of more than 1m depth was excluded to avoid issues with appearance and daylighting. Shading optimisation parameters can be found in Table 4.16 in the Methodology Chapter.

Influence of Window Shading on Cooling and Heating Energy Consumption

The effectiveness of adding external shading devices depends on the season, as illustrated in Figure 7.41. During summer, all of the selected solar devices reduce cooling energy, and the surrounding shading devices contribute to the highest reductions, in which 9.1%, 10.6% and 12.4% reductions are achieved from using surrounding shading at 0.3m, 0.5m, and 1m projection depths, respectively. On the other hand, a reverse result is produced by solar shading devices in the winter, whereby heating energy increases by up to 0.9%, 1.4%, and 2.5% respectively using surrounding shading at 0.3, 0.5m, and 1m projection depths. Nevertheless, as the reduction in cooling energy outweighs the rise in heating energy, solar shadings can still be employed.

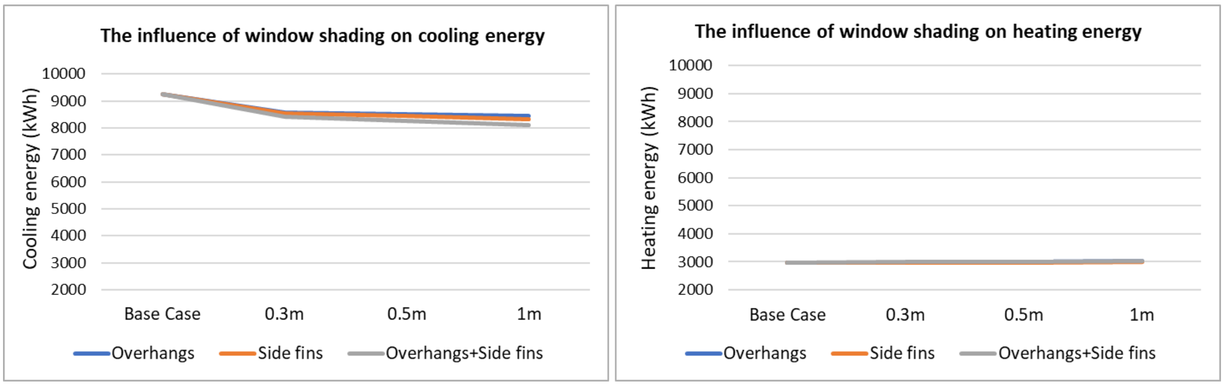


Figure 7. 41 Influence of local shading devices on cooling and heating energy consumption

Influence of Window Shading on Comfort Hours in Summer and Winter.

The application of solar shading devices has no noticeable effect on the percentage of comfort hours in summer with a less than 1% increase in the percentage of comfort hours produced by all shading types. Also, in the winter, a less than 1% reduction in percentage comfort hours can be seen with all shading types. However, the percentage of comfort hours is still within the acceptable limit of ASHRAE standards 55 in both summer and winter (Figure 7.42).

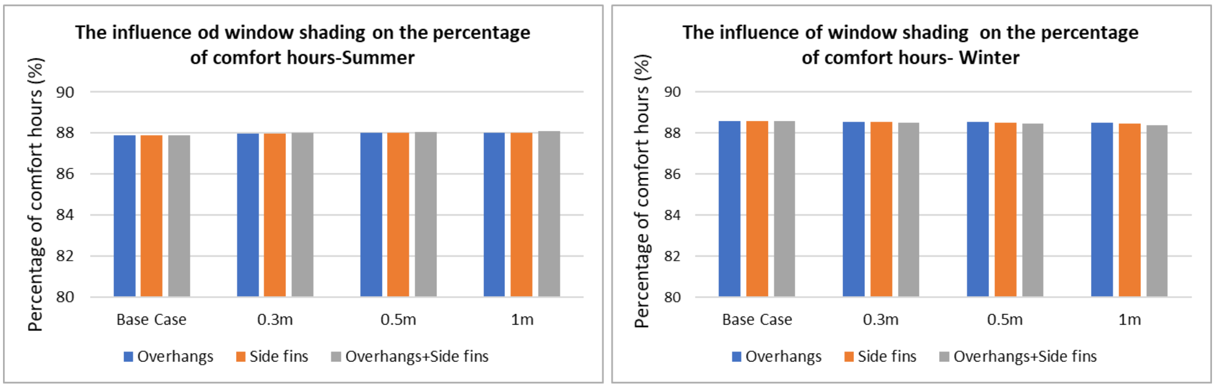


Figure 7. 42 Influence of window shading on the percentage of comfort hours during summer and winter

Influence of Window Shading on Indoor Temperature in Summer and Winter

It can be clearly seen from Figure 7.43 that optimising the windows with surrounding shading at different projection depths has no influence on indoor temperatures during either summer or winter. This is attributed the limited solar gain through the windows due to the low window to wall ratio.

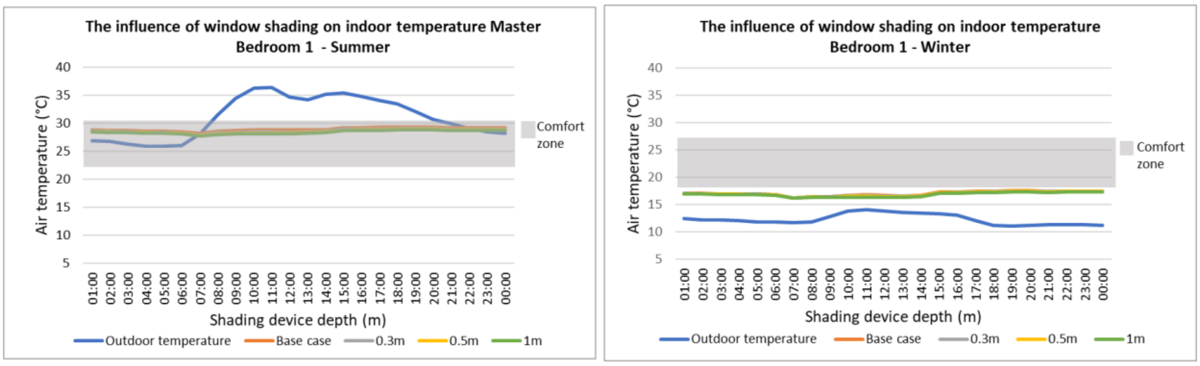


Figure 7. 43 Influence of solar shading devices on the percentage of comfort hours in summer and winter

7.3.2.2 Stage 2 Optimisation Results

A combination of moderate and extreme values of different parameters helps reduce energy demand from 17541.33 kWh/y to 6934.24 kWh/y. The first simulation includes 1792 iterations, of which the Pareto front produces 35 optimal solutions (Figure 7.44). The range of site energy consumption for the optimal solutions is from 8118.70 kWh/y to 6934.24 kWh/y, and none of the provided optimal solutions compromise thermal comfort. The second simulation includes 1783 iterations, of which the Pareto front produces 69 optimal solutions (Figure 7.45). The range of the site's energy consumption for the optimal solutions is 8387.44 kWh/y to 6965.63 kWh/y. It is found that the position of the insulation material, whether internally or externally placed, does not differ substantially in terms of energy use reduction.

Optimal retrofit solutions

The most optimal design solution, which produces the lowest site energy consumption with an acceptable range of 89.26 % annual comfort hours at 60.5 % energy reduction, includes the following design parameters:

- Roof with external insulation with a U-value of 0.1 W/m².K,
- Walls with external insulation with a U-value of 0.1 W/m².K,
- 'Trp Clr 3mm/13mm Arg' glazing with a U-value of 1.6 W/m².K and SHGC of 0.68.

- Side fins of 0.5m + 0.5 overhang for shading the NE windows, side fins of 0.3m for shading the SE windows, and side fins of 0.5m + 0.5 overhang for shading the NW windows.

The optimal simulation, improving indoor thermal comfort to 90.2 % annual comfort hours at 53.71% energy reduction includes the following design parameters:

- Roof with external insulation with a U-value of 0.1 W/m² K,
- Walls with external insulation with a U-value of 0.4 W/m² K.
- 'Trp Clr 3mm/13mm Arg ' glazing with a U-value of 1.6W/m².K and SHGC of 0.68.
- 0.3 overhang for shading the NE windows, side fins of 0.3m for shading the SE windows, and side fins of 0.5m + 0.5 m overhang for shading the NW windows.

The primary energy consumption of the base case model is reduced from 226 kWh/m²/y to about 138.72 kWh/m²/y, and cooling and heating energy demand is reduced from 122.1 kWh/m²/y to 36 kWh/m²/y, thereby nearly meeting the Passivhaus targets for retrofits.

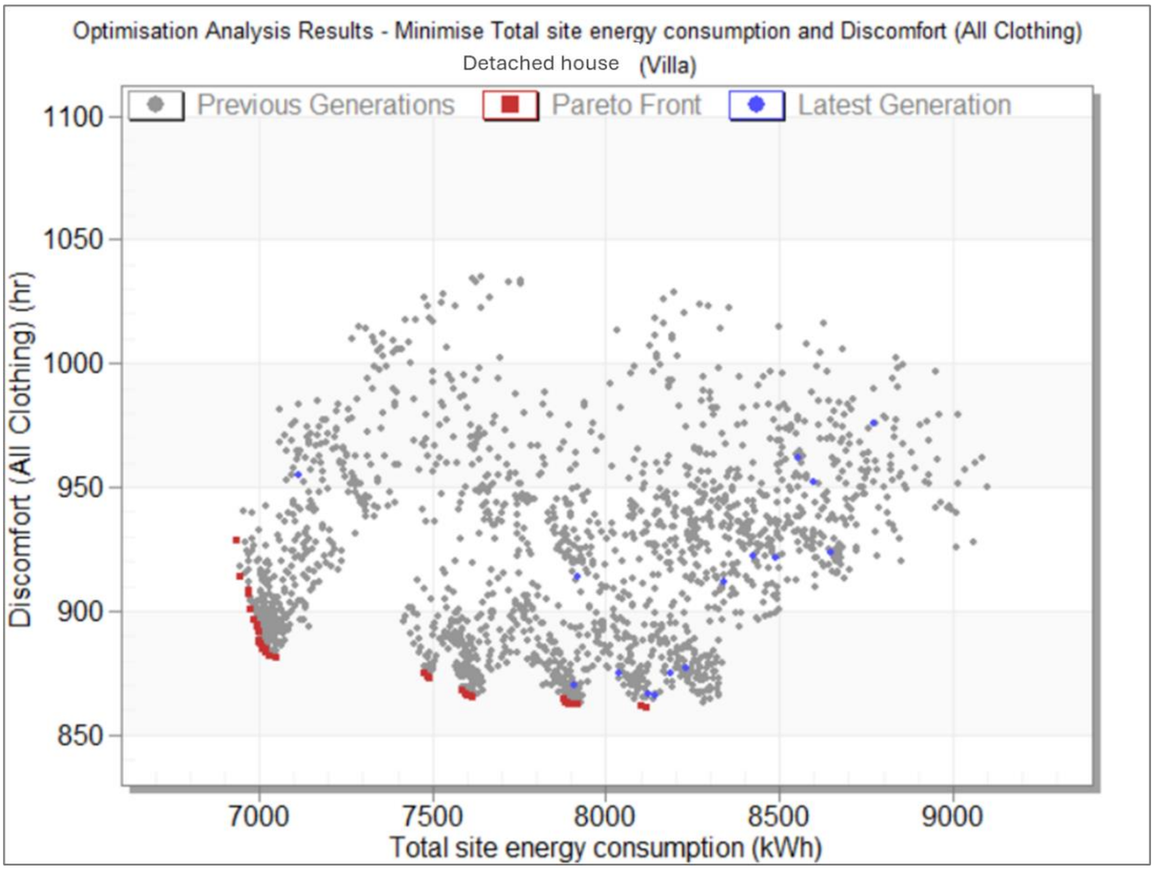


Figure 7. 44 Multi-objective optimisation result 1,- Case Study 2.

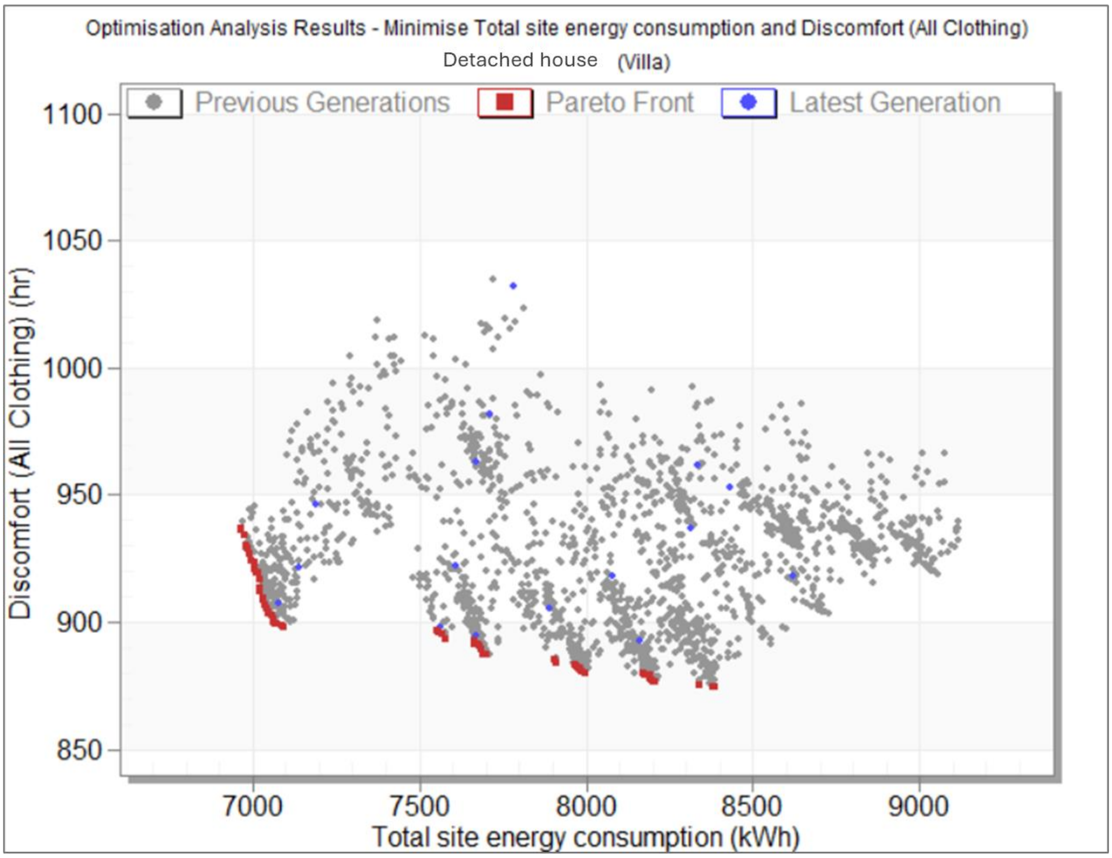


Figure 7. 45 Multi-objective optimisation result 2, Case Study 2.

Influence of Optimal Retrofit Solution on Indoor Temperature - Case Study 2

This section studies the influence of the optimal solution on indoor temperature for Case Study 2 during summer and winter. The optimal solution includes an upgraded roof and walls with insulation at a U-value of 0.1 W/m^2 K, which may in practice be difficult to apply because it requires a thick insulation material ranging between 0.36 m and 0.48 m. This thickness requires sufficient space, whether inside or outside the building, for its application. Therefore, a second simulation run was conducted to investigate the effect of the optimal solution on indoor temperature but with a roof and wall U-value at 0.5 W/m2 K, which requires a lower insulation thickness of between 0.061m and 0.079m.

As illustrated in Figure 7.46, the simulation results for the summer show that the optimal solution can achieve a remarkable reduction in indoor temperature of between 4.1 °C and 6.1°C in bedroom 1, at wall and roof U-values of 0.5 W/m^{2}K and 0.1 W/m^{2}K, respectively, to bring the indoor temperature to a comfortable level. Similarly, in winter, a noticeable increase in indoor temperature is witnessed. For instance, the temperature in bedroom 1 is increased by 2.3°C at a wall and roof U-value of 0.5 W/m^2 K. The temperature is increased further with a wall and floor U-value of 0.1 W/m^{2}K, to achieve a 3.4°C increase in indoor temperature, and making the indoor temperature comfortable.

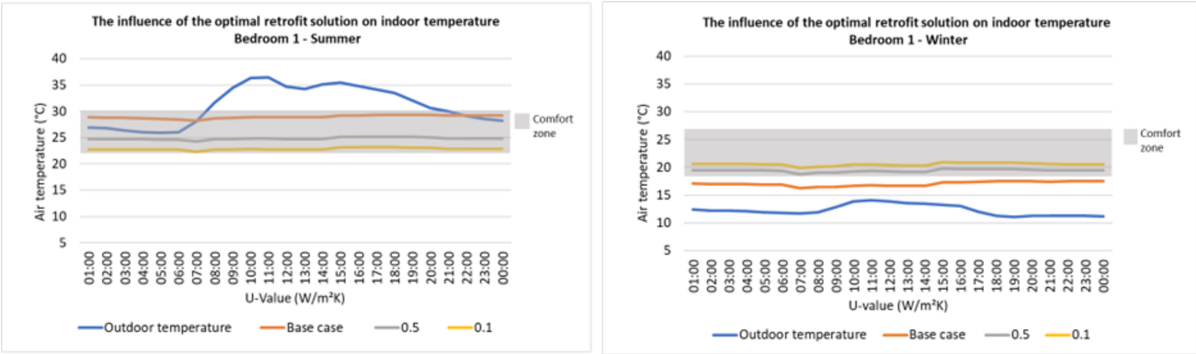


Figure 7. 46 Influence of the optimal retrofit solution on indoor temperature in summer and winter

7.3.2.2.1 Further optimisation scenarios

- **Further energy reductions from adjusting cooling and heating set points based on the acceptable comfort ranges of ASHRAE Standard 55**

According to ASHRAE 55 standards, indoor thermal comfort in Libya ranges from 22°C to 30°C in summer, and from 19°C to 26°C in winter. This means that individuals can feel comfortable at 26 °C in the summer and at 22°C in winter. However, based on the building survey, the cooling set point is set at 22°C, which represents the lower band of comfort level in the summer, while in winter, the heating set point is set at 26°C, and 23°C in the bedrooms, and the master bedroom respectively. If the set points of the base case model are adjusted based on an acceptable temperature for comfort in the summer and winter, more energy reductions can be achieved.

To investigate this, the optimised Case Study 2 is further optimised by adjusting the cooling set point to 26 °C and the heating set point to 22 °C. The simulation results show that adjusting the cooling and heating set points of the optimised model achieves an 8.9% additional site energy reduction. Primary energy demand is reduced further from 138.72 kWh/m²/y to 119.27 kWh/m²/y, cooling and heating energy demand is reduced further from 36 kWh/m²/y to only 16.6 kWh/m²/y, meeting the Passivhaus target for retrofits.

- **Energy retrofit solution with roof and wall insulation only**

A passive retrofit solution that only incorporates roof and wall insulation achieves a 41.9% site energy reduction at roof and a wall U-value of 0.5 W/m² K. Primary energy demand is reduced from 226 kWh/m²/y to 157.68 kWh/m²/y, while primary cooling and heating energy demand is reduced from 122.1 kWh/m²/y to 53.65 kWh/m²/y. At a roof and wall U-value of 0.1, greater energy reduction is achieved. Site energy consumption is reduced by 58.68%, primary energy demand is reduced from 226 kWh/m²/y to 140.20 kWh/m²/y, while cooling and heating energy is reduced from 122.1 kWh/m²/y to 37.49 kWh/m²/y, nearly meeting the Passivhaus target for retrofits.

Optimisation of the Base Case Study 1 Model as a Fully Conditioned Building.

When optimising the base case model as a fully conditioned building using the optimal retrofit solution, it is found that primary energy consumption is reduced from 267.4 kWh/m²/y to 143.01 kWh/m²/y. Site cooling and heating energy demand is reduced from 162.77 kWh/m²/y to 87.04 kWh/m²/y. By adjusting the cooling and heating setpoints based on the acceptable comfort range for Libya, additional energy reductions are achieved. The cooling set point is adjusted from 22 °C to 26 °C, and the heating set point is adjusted from 26° C to 22° C. The simulation results show that optimising the set points can achieve further energy reduction, and meet the Passivhaus target for retrofits, where primary energy consumption is reduced to 127 kWh/m²/y, and primary cooling and heating energy demand is reduced to 31.28 kWh/m²/y.

7.3.2.3 Stage 3 Optimisation Results

This section explores the potential for meeting the requirements of net zero energy buildings for Case Study 2 by adding a PV performance model in DesignBuilder. As mentioned in Section 7.3.2.1 thermally renovating the building envelope could contribute to a 60.5% reduction in the site's energy consumption. To meet the remaining 39.5% of the energy needed to achieve the target of NZEBs, solar panels of 400W were installed on the roof. The simulation results show that the photovoltaic system consists of 10 solar panels of 400W arranged in one line with a total area of 20 m^2 to meet the remaining energy needs and achieve NZEBs requirements. In addition, there remains adequate space on the roof for an additional 10 solar panels to supply the energy requirements of an additional storey. Figure 7.47 shows the locations and areas for the installation of photovoltaic panels on the roof of Case Study 1. Table 7.3 shows a range of solutions, including the optimal solutions, the resultant energy conservation, and the number of solar panels required to achieve an NZEBs target for each solution.

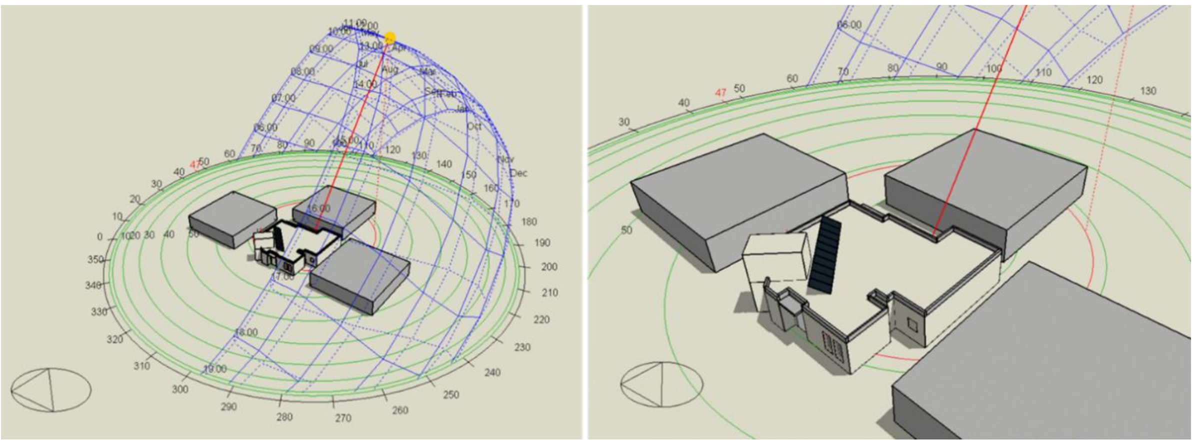


Figure 7. 47 Photovoltaic panel arrangement- Case Study 2

Table 7. 3 The optimal retrofit solutions and number of solar panels needed to meet NZEBs- Case Study 2

	Site energy consumption (kWh)	Percentage of comfort hours (%)	Primary energy demand (kWh/m²/y)	Primary cooling and heating Energy demand (kWh/m²/y)	U-Value (W/m²k) Wall; Roof	Saving (%)	Remaining energy need %	No. of Panels to NZEB
The optimal solution	6934.24	89.26	138.72	36	0.1; 0.1	60.50	39.50	10
The optimal solution with different wall and roof U-values	7660.59	89.80	141.27	37.72	0.2 0.2	56.33	43.67	11
	8194.521	89.90	145.53	41.72	0.3;0.3	53.28	46.72	11
	8757.29	90.0	149.28	45.33	0.4;0.4	50.08	49.92	12
	9058.03	90.1	153.15	49.13	0.5;0.5	48.36	51.64	13
The optimal solution + adjustment of cooling and heating set points	5367.82	88.11	119.27	16.6	0.1; 0.1	69.40	30.60	8
	6810.51	86.76	129.40	25.38	0.5;0.5	61.17	38.83	10
Roof and wall insulation only	7246.81	89.53	140.20	37.49	0.1; 0.1	58.69	41.31	11
	10178.58	88.62	157.68	53.65	0.5;0.5	41.97	58.03	14

7.3.3 Case Study 3- Optimisation Results

7.3.3.1 Stage 1 Optimisation Results

7.3.3.1.1 Roof insulation

This section examines the impact of upgrading the base case roof with insulation materials. The existing roof in Case Study 3 has a U-value of 2.05 W/m²K. The U-values selected in order to optimise the building range between 0.5 W/m²K and 0.1 W/m²K, in 0.1 decrements. The analysis also considers the effect of the insulating materials' position, both inside and outside. The specifications of the optimised roof with insulation materials at different thicknesses are described in Table 4.14 in the Methodology Chapter.

Influence of Roof Insulation on Cooling and Heating Energy consumption

Based on Figure 7.48, reducing the U-value of the roof by adding biobased insulation materials leads to a decrease in cooling and heating energy. Reducing the base case U-value of the roof to 0.5 W/m²K through internal insulation reduces cooling and heating energy by 6.4% and 14.7%, respectively. Cooling and heating energy continue to decline as the U-value is reduced further, reaching 9.5% and

17.96% respectively at 0.1 W/m²K. External insulation has similar influence on cooling and heating energy compared to internal insulation, where a U-value of 0.5 W/m²K reduces cooling energy by 6.5% and heating energy by 14.6%. As the U-value decreases further, cooling energy and heating energy are also decreased further, reaching 9.7% and 18.7%, respectively. Consequently, implementing wall insulation is effective in reducing energy use regardless of whether it is applied internally or externally. The four insulating materials each reduce the cooling and heating energy by comparatively similar percentages due to the similarity of their thermal properties.

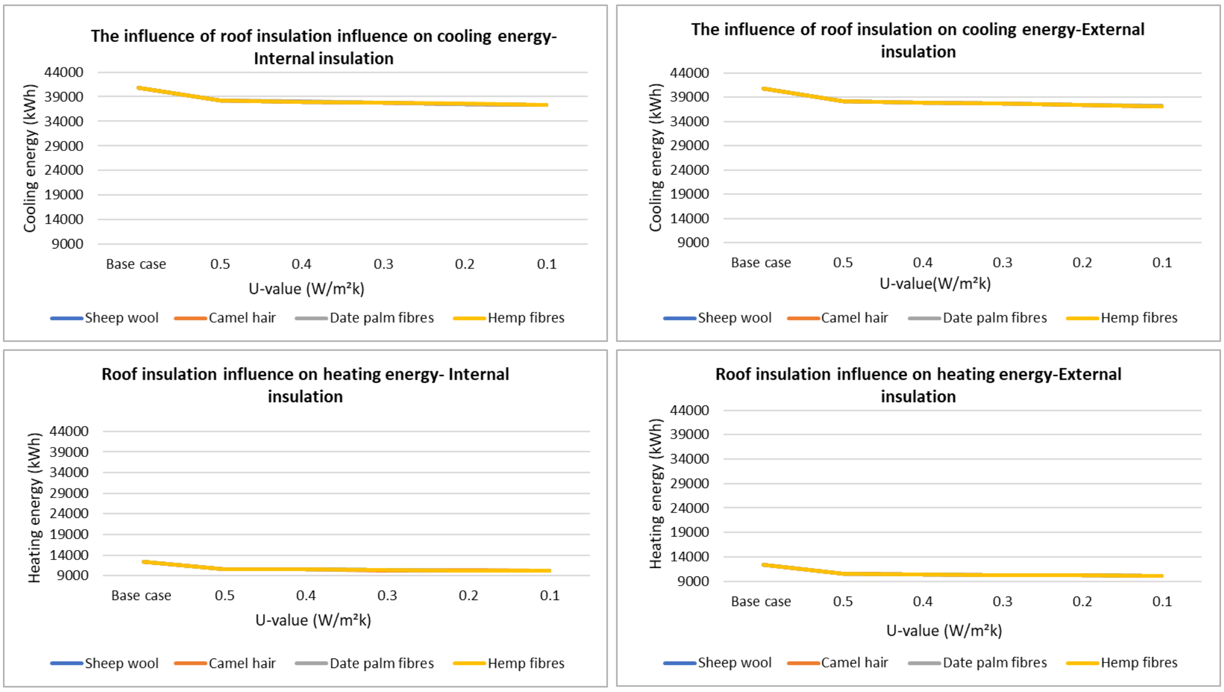


Figure 7. 48 Influence of roof insulation on cooling and heating energy consumption

Influence of Roof Insulation on Comfort Hours in Summer and Winter.

Figure 7.49 shows that, regardless of whether the insulation materials are applied internally or externally, insulation material slightly improves the thermal comfort of indoor spaces in the summertime, in which the percentage of comfort hours in the summer is increased by only 1.5%. However, this minor increase does not bring indoor conditions to within acceptable limits as set by ASHRAE Standard 55. On the other hand, in winter, the percentage of comfort hours of the base case falls within acceptable ASHRAR 55 limits, while with insulating the roof, the percentage of comfort hours is improved by 1% only, and remains within the acceptable percentage of comfort hours.

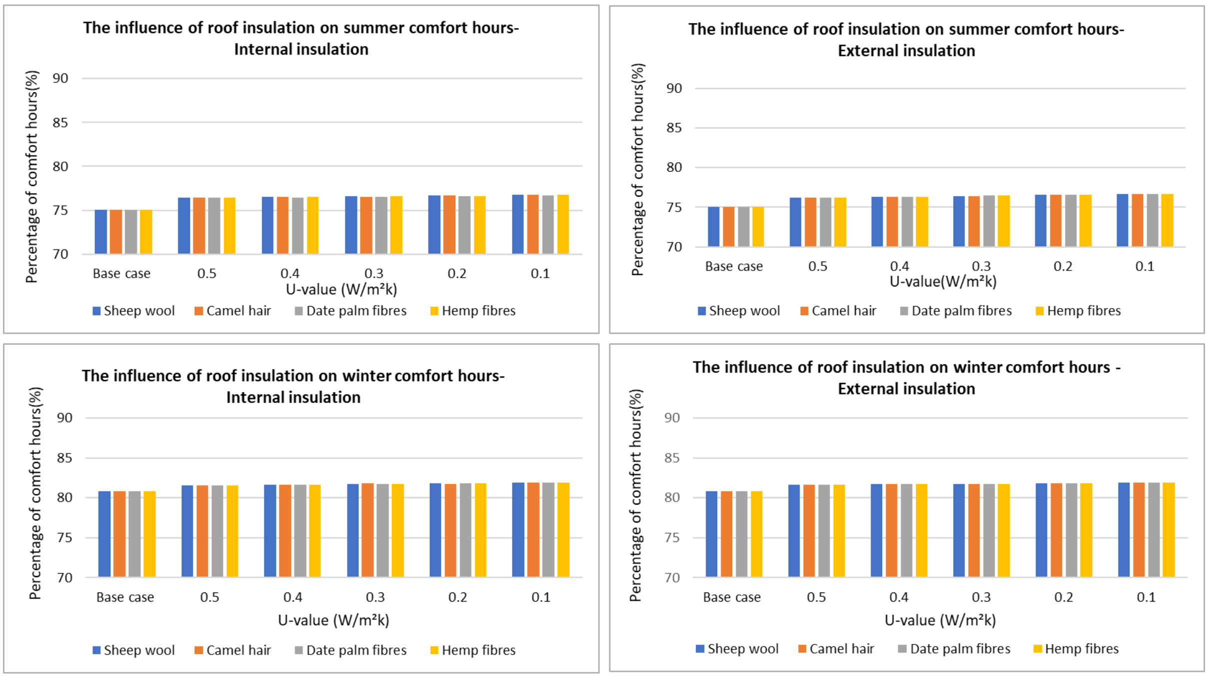


Figure 7. 49 Influence of roof insulation on the percentage of comfort hours during summer and winter

The Influence of Roof Insulation on Indoor Temperature in Summer and Winter

Figure 7.50 shows that roof insulation slightly influences indoor temperatures in both summer and winter. For instance, the bedroom witnesses a slight decrease in indoor temperature in the summer, of 0.5 °C and 0.8 °C at wall U-values of 0.5 W/m²K and 0.1 W/m²K, respectively. Similarly, in the winter, a modest increase of up to 0.7°C in indoor temperature is achieved when the U-value is reduced to 0.1 W/m²K. However, despite this change, the temperatures in the summer and winter are still uncomfortable.

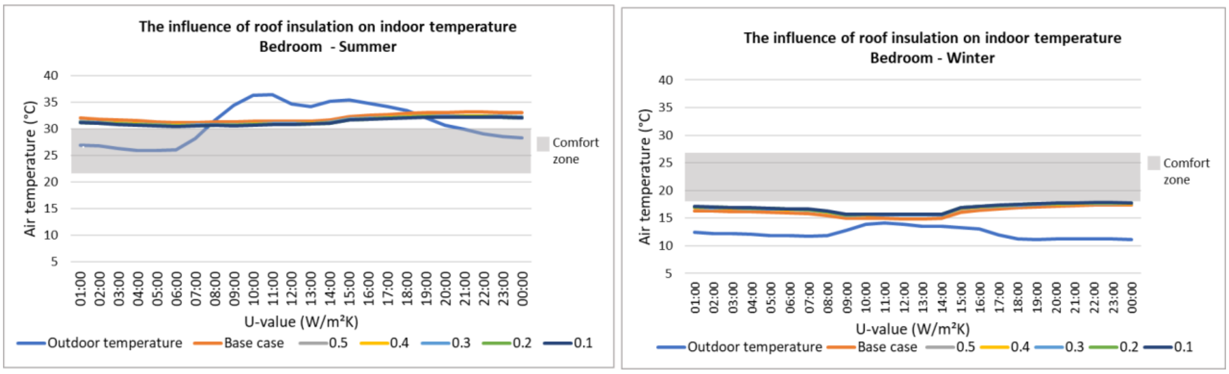


Figure 7. 50 Influence of roof insulation on indoor temperature in summer and winter

7.3.3.1.2 External wall insulation

This section examines the impact of upgrading the walls with insulation materials. The base walls of Case Study 3 have a U-value of 2.61 W/m²K. The U-values selected for optimising the building walls range between 0.5 W/m²K and 0.1 W/m²K, set at decrements of 0.1. The specifications of the optimised walls with insulation materials at different thicknesses are described in Table 4.14 in the Methodology Chapter.

Influence of External Wall Insulation on Cooling and Heating Energy Consumption

Following the investigation of the savings potential for cooling and heating energy using roof insulation, the influence of insulating the external walls is studied. Wall insulation, as shown in Figure 7.51, contributes to a relatively effective cooling and heating energy reduction. Reducing the base case U-value of the walls to 0.5 W/m²K through internal insulation reduces cooling energy use by up to 28.3%. This reduction in cooling energy continues as the U-value is reduced further, reaching 39.1% energy reduction at a U-value of 0.1 W/m²K. External application of wall insulation has a slightly more influence than internal insulation on cooling energy, in which reductions of around 28.4% and 40.8% are achieved at wall U-values of 0.5 W/m²K and at 0.1 W/m²K, respectively. Internal and external insulation decrease heating energy by 59 % 56.3 %, respectively at wall U-values of 0.5 W/m²K, and the decrease continues with an increase in insulation thickness, reaching up to 70.3 % and 71% with internal and external insulation, respectively, at a wall U-value of 0.1 W/m²K. Thus, the implementation of wall insulation has a noticeable influence in terms of reducing energy regardless of whether it is applied internally or externally. The four insulating materials each reduce cooling and heating energy by comparatively similar percentages due to similarity in their thermal properties.

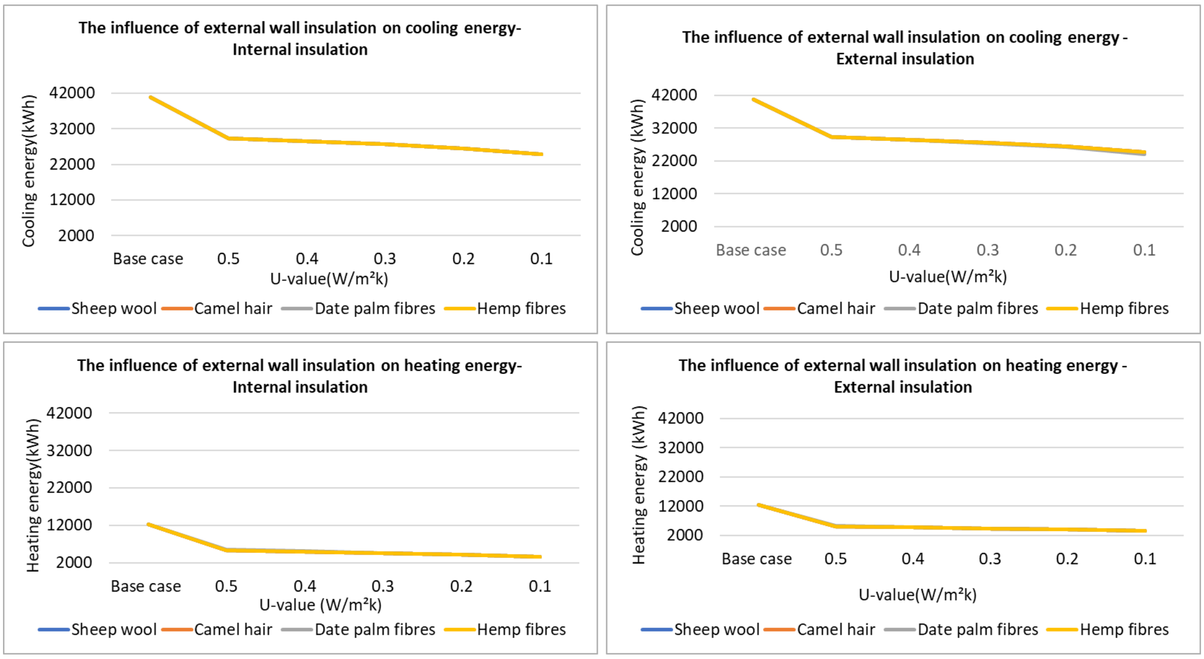


Figure 7. 51 Influence of wall insulation on cooling and heating energy consumption

Influence of Wall Insulation on Comfort Hours in Summer and Winter

A modest increase is seen in the percentage of comfort hours of up to 2.5% at a wall U-value of 0.1 W/m²K during the summer, whether wall insulation materials are placed internally or externally (Figure 7.52). However, the percentage of comfort hours remains below the acceptable percentage of comfort hours. Conversely, in winter, the percentage of comfort hours is improved noticeably: by up to 8% at a wall U-value of 0.1 W/m²K, regardless of whether the insulation is placed internally or externally.

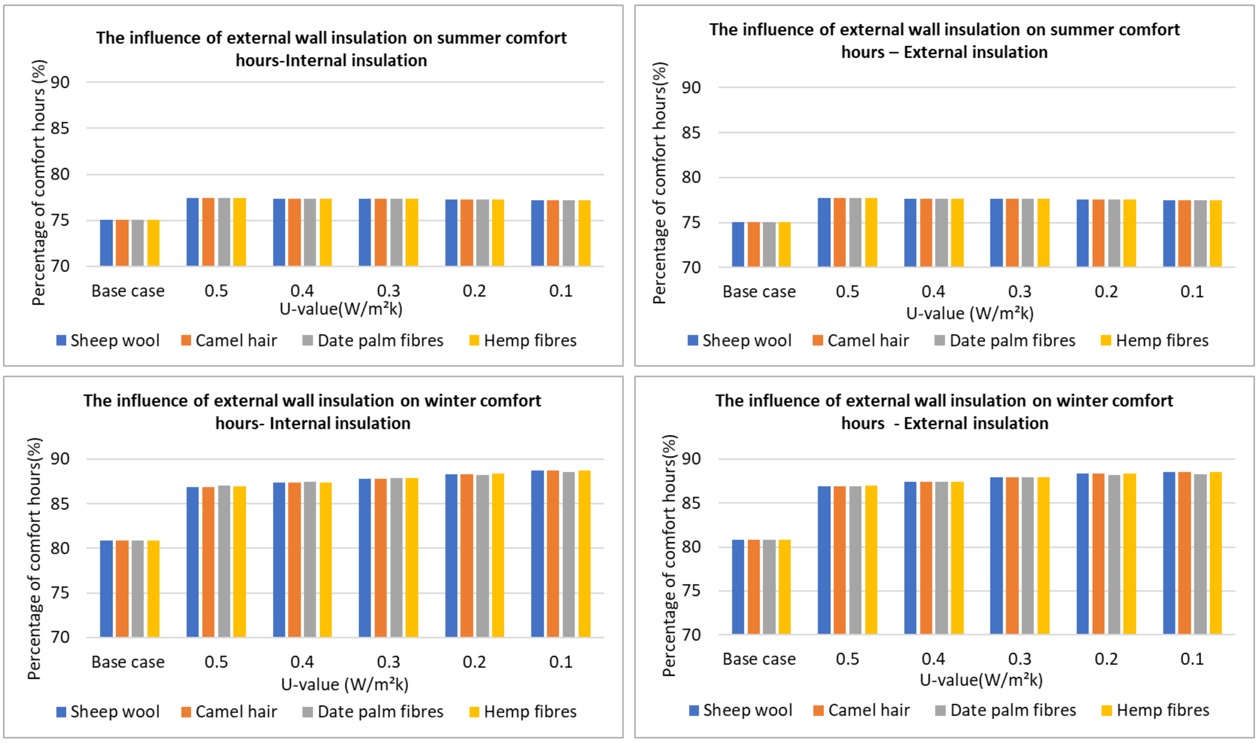


Figure 7. 52 Influence of wall insulation on comfort hours during summer and winter

Influence of External Wall Insulation on Indoor Temperature in Summer and Winter

As illustrated in Figure 7.53, insulating the external walls contributes to a decrease in the indoor temperature in the summer of 1°C at a wall U-value of 0.5 W/m²K and of 1.4°C at a wall U-value of 0.1 W/m²K. In the winter, an increase is seen in indoor temperature of up to 2 °C at a wall U-value of 0.5 W/m²K, and of up to 2.8°C at a wall U-value of 0.1 W/m²K.

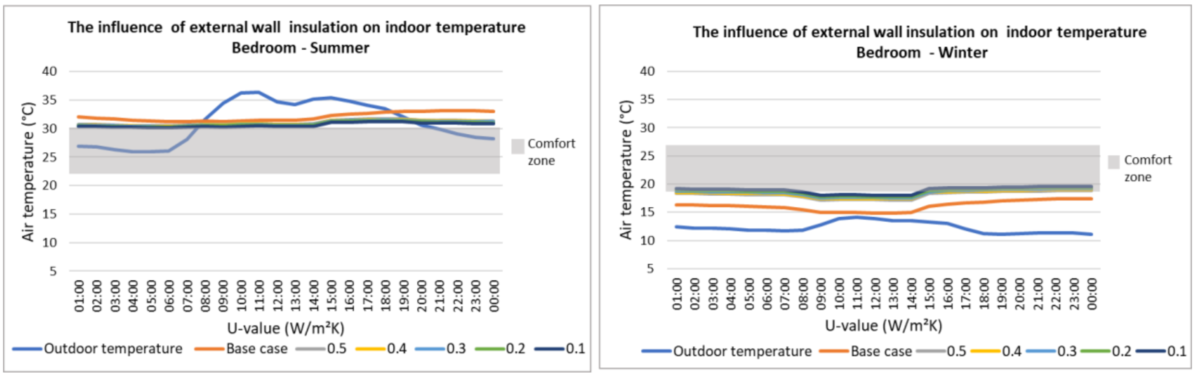


Figure 7. 53 Influence of external wall insulation on indoor temperature in the summer and winter

7.3.3.1.3 Ground Floor Insulation

This section involves an investigation of the influence of insulation materials when applied to the internal surface of the ground floor. The base case ground floor has a U-value of 1.5 W/m²K. The U-values selected for optimising the internal surface of the ground floor range between 0.5 W/m²K and 0.1 W/m²K, in decrements of 0.1. The specifications of the optimised ground floor slab with insulation materials are described in Table 4.14 in the Methodology Chapter.

Influence of Ground Floor Insulation on Cooling and Heating Energy

Ground floor insulation, as shown in Figure 7.54, contributes to an increase in cooling energy, with approximately a 9.9% increase is witnessed at a floor U-value of 0.5 W/m²K. The increase in cooling energy continues with decreases in the floor U-value, to reach 14.5% at a U-value of 0.1 W/m²K. This increase in cooling energy occurs because without insulation materials, the ground acts as a heat sink without insulation, and insulating the floor leads to increase the cooling energy. Conversely, heating energy shows about a 3.6% decrease at a floor U-value of 0.5 W/m²K, and as the U-value decreases, the heating energy is reduced more by 4.5% at 0.1 W/m²K. However, because the increase in the cooling energy is much greater than the decrease in heating energy, it is not recommended to insulate the ground floor, but rather to keep it uninsulated to utilise the thermal mass of the floor and help reduce the cooling energy. Therefore, ground floor insulation is exempted from the multi-objective optimisation stage.

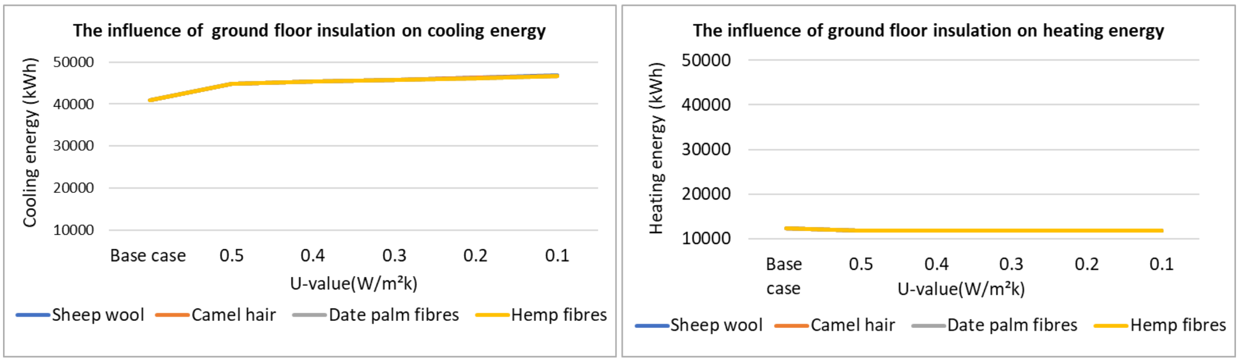


Figure 7. 54 Influence of ground floor insulation on cooling and heating energy

Influence of Ground Floor Insulation on Comfort Hours in Summer and Winter

With regard to indoor thermal conditions, there is up to a 1% decrease in the percentage of comfort hours with ground floor insulation at a U-value of 0.1 W/m²K in the summer. On the other hand, insulating the ground floor does not show an influence during the winter, and the percentage of comfort hours remains stable and within the acceptable limits set by ASHRAE 55 (Figure 7.55).

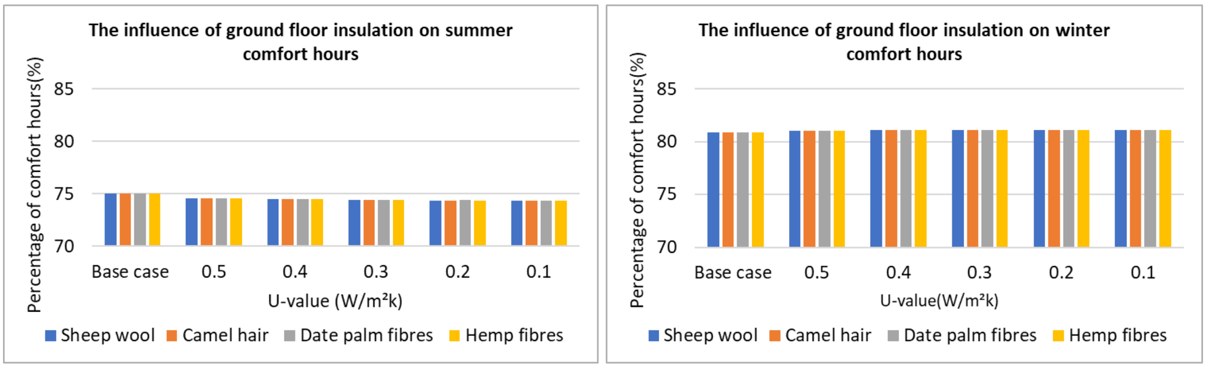
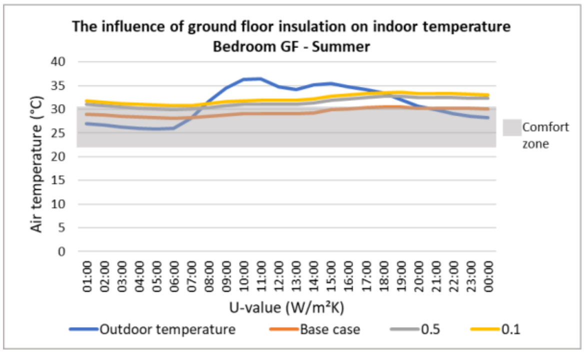


Figure 7. 55 Influence of ground floor insulation on comfort hours during summer and winter

Influence of Ground Floor Insulation on Indoor Temperature in Summer and Winter

The bedroom on the ground floor is selected to investigate the impact of floor insulation on indoor temperatures. Insulating the ground floor has a noticeable impact on indoor temperature during the summer only (Figure 7.56). The indoor temperature of the bedroom witnesses increases of about 2.7 °C and 3.7 °C respectively at floor U-values of 0.5 W/m²K and 0.1 W/m²K, making the indoor temperature hotter, which will lead to an increase in cooling energy during the summer. Conversely, in winter, no impact is seen on indoor temperature from insulating the ground floor. This result confirms that the ground floor should not be insulated.



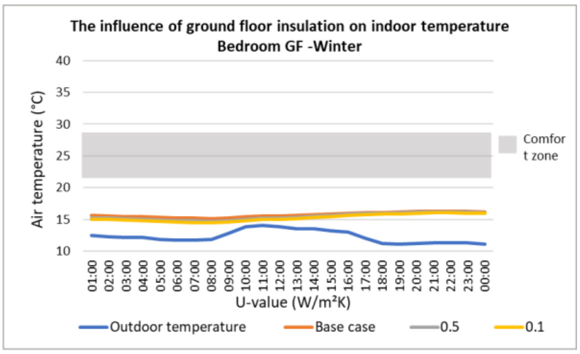


Figure 7. 56 Influence of ground floor insulation on indoor temperature in summer and winter

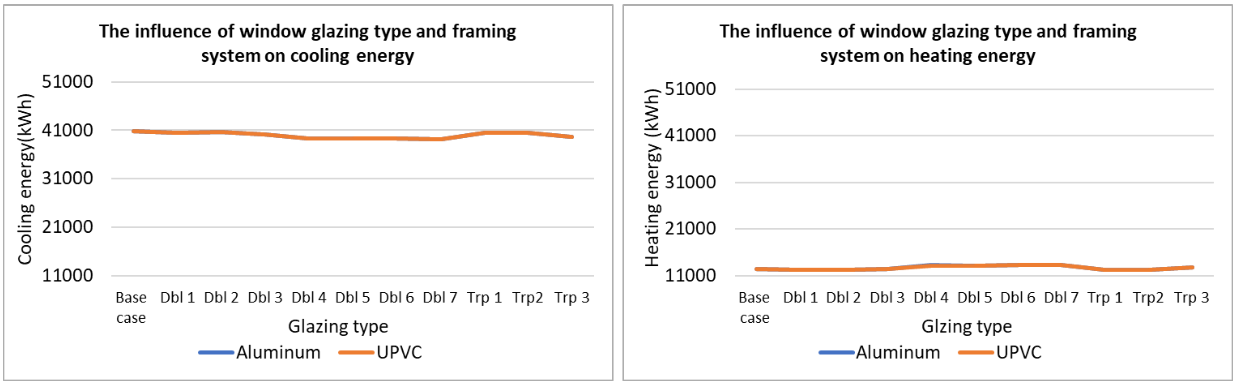
7.3.3.1.4 Window glazing type and framing system

In previous sections, the upgrading of opaque envelope materials by adding insulation has been discussed. In this section, the effects of renovating the window glazing type and framing system are examined. The base case window glazing type is 6m single clear glass with aluminium framing, and this is upgraded using seven types of double glazing and three types of triple glazing with different thermal and solar characteristics, and UPVC framing systems. Energy-efficient glazing types that affect light transmission are excluded. The solar and thermal properties of the existing glazing type and glazing types used for optimising the windows are described in Table 4.15 in the Methodology Chapter.

Influence of window glazing type and frame on cooling and heating energy

All of the selected types of glazing reduce cooling energy (Figure 7.57). Both aluminium framing and UPVC framing systems show the same influence on cooling and heating energy. Moreover, the solar factor of the glazing has more influence compared to the U-value of the glazing. Double reflective glazing, which has the property of reflecting solar radiation, has a higher U-value than double and triple clear glazing: however, reflective glazing types achieve a higher reduction in cooling energy. For instance, reflective double glazing (Dbl 4, Dbl 5, Dbl 6, Dbl 7) that has the lowest solar factor (LSF) and the highest U-value produces the highest reductions in cooling energy, of up to 3.9%, followed by triple (Trp3) low emissivity glazing that has a higher solar factor (MSF) and a lower U-value, which results in a cooling energy reduction of 2.8%. Double (Db1, Db2) and triple (Trp1, Trp2) clear glazing types which have the highest solar factor (HSF) give cooling energy reductions of only 1.8% and 1%, respectively. In contrast, the reflective glazing type with a low solar factor (LSF) slightly raises heating energy, by up to 8.02%. This is because the reflective film blocks the solar heat from warming the interior in winter, leading to more heating energy consumption. Other glazing types produce a minor reduction in heating energy, in which only a 1.3% reduction is produced by triple clear glazing (Tpr2).

Generally, reflective glazing, although slightly increasing heating energy, more significantly reduces cooling energy. Triple clear with air filling (Tpr1) and triple clear with argon filling (Tpr2) produce both cooling and heating energy reductions. However, these reductions in cooling and heating energy are considered minor, with only 0.7 %and 1.6% reductions achieved respectively.

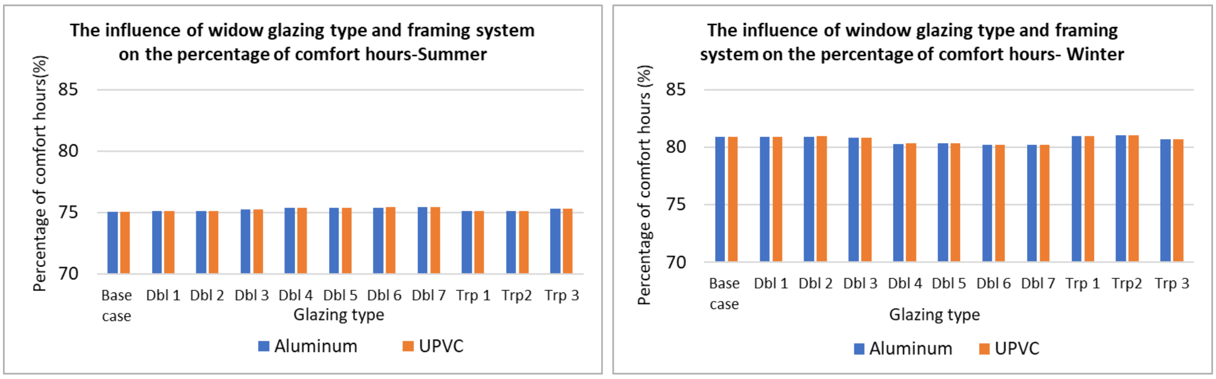


Base case: Sgl Clr 6mm, **Dbl 1**: Dbl Clr 6mm/13mmAir, **Dbl 2**: DblClr/6mm/13mmArg, **Dbl 3**: Dbl LoE Clr 6mm/13mm Arg, **Dbl 4**: Dbl Ref Clr 6mm/13mm Air, **Dbl 5**: Dbl Ref-D Clr 6mm/13mm Arg, **Dbl 6**: Dbl Ref-D Tint 6mm/13mmAir, **Dbl 7**: Dbl Ref-D Tint 6mm/13mm Arg, **Trp 1**: Trp Clr 3mm/13mm Air, **Trp 2**: Trp Clr 3mm/13mm Arg **Trp 3**: Trp LoE Clr 3mm/13mm Arg

Figure 7. 57 Influence of window glazing type and framing system on cooling and heating energy

Influence of Glazing Type and Framing System on Comfort Hours in Summer and Winter

Upgrading of window type does not show an important effect on the percentage of comfort hours during the summer, and a less than 1% increase in the percentage of comfort hours is achieved using any type of energy-efficient glazing. On the other hand, a minor decrease in the percentage of comfort hours in the heating season is demonstrated by all reflective glazing windows. This is because reflective glazing blocks the solar heat from warming the interior, leading to around a 1% reduction in comfort hours. However, the percentage of comfort hours remains within the acceptable limits of ASHRAE 55 (Figure 7.58).



Base case: Sgl Clr 6mm, **Dbl 1**: Dbl Clr 6mm/13mmAir, **Dbl 2**: DblClr/6mm/13mmArg, **Dbl 3**: Dbl LoE Clr 6mm/13mm Arg, **Dbl 4**: Dbl Ref Clr 6mm/13mm Air, **Dbl 5**: Dbl Ref-D Clr 6mm/13mm Arg, **Dbl 6**: Dbl Ref-D Tint 6mm/13mm, **Dbl 7**: Dbl

Ref-D Tint 6mm/13mm Arg, **Trp 1**: Trp Clr 3mm/13mm Air, **Trp 2**: Trp Clr 3mm/13mm Arg **Trp 3**: Trp LoE Clr 3mm/13mm Arg

Figure 7. 58 Influence of window glazing type and framing system on the percentage of comfort hours during summer and winter

Influence of Window Glazing Type on Indoor Temperature in Summer and Winter

It can be clearly seen in Figure 7.59 that optimising the window glazing with energy efficient glazing types has no influence on indoor temperatures during the summer and winter. This is attributed to the limited solar gain through the windows due to the low window to wall ratio.

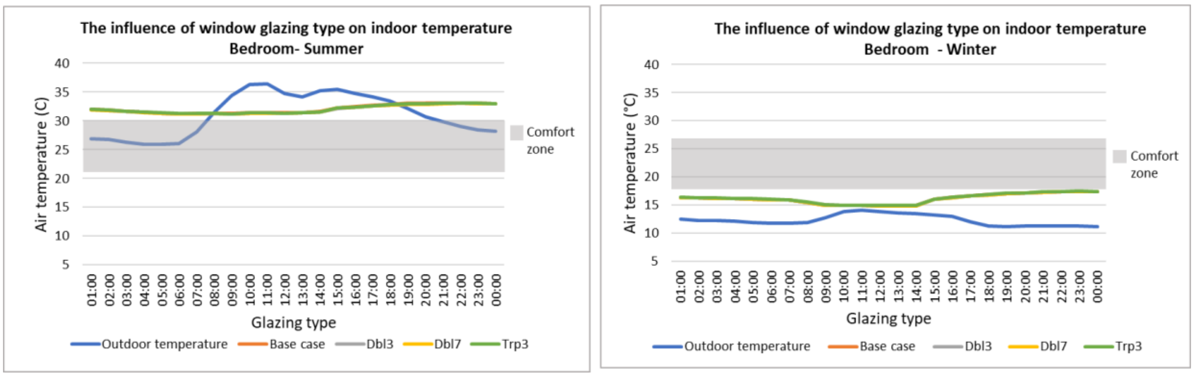


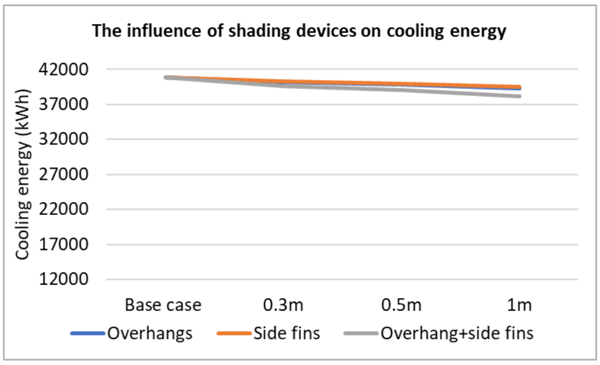
Figure 7. 59 The influence of window glazing type on indoor temperature in summer and winter

7.3.3.1.5 Local shading devices

This section investigates the impact of fixed shading devices on heating and cooling energy. Case study 3 has no window shading. In order to optimise the window with local shading, three types of fixed shading devices are studied: overhangs, side fins, and surrounding shading (overhangs + side fins) to control solar gain through the windows. The length of horizontal and vertical projection ranges between 0.3m and 1m. Solar shading with more than 1m depth is excluded to avoid issues with appearance and daylighting. Shading optimisation parameters can be found in Table 4.16 in the Methodology Chapter.

The influence of window shading on cooling and heating energy

The effectiveness of adding external shading devices depends on the season, as illustrated in Figure 7.60. During the summer, window shading contributes to cooling energy reductions, with 4.4% and 6.5% energy reductions produced by surrounding shading at 0.5m and 1m projection depths, respectively. However, a reverse effect of the window shading can be seen in the winter, where heating energy witnesses increases of 9% and 15.4% using surrounding shading at 0.5m and 1m projection depths, respectively. However, solar shadings can still be used because the decrease in cooling energy is much greater than the increase in heating energy.



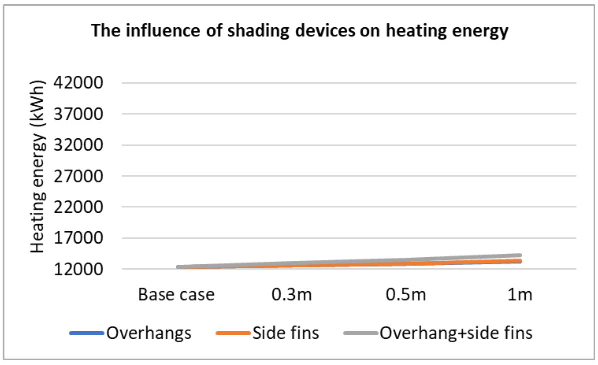
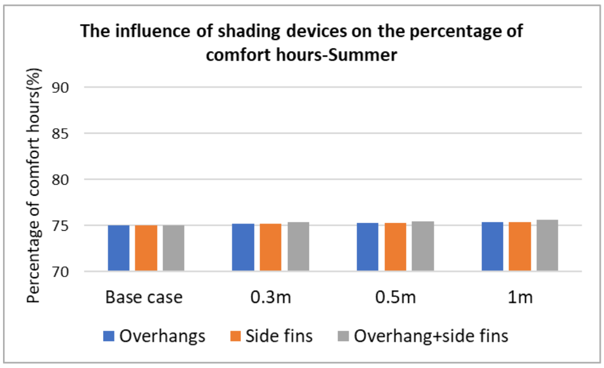


Figure 7. 60 The influence of window shading on cooling and heating energy

Influence of Solar Shading on Comfort Hours in Summer and Winter

The application of solar shading devices has a minor effect on indoor thermal conditions in the summer season, where the percentage of comfort hours is increased by only 0.5% and does not bring indoor conditions to within acceptable limits as set by ASHRAE 55. In the winter, window shading does not affect indoor thermal comfort, and the percentage of comfort hours remains within the acceptable range set by ASHRAE 55 (Figure 7.61).



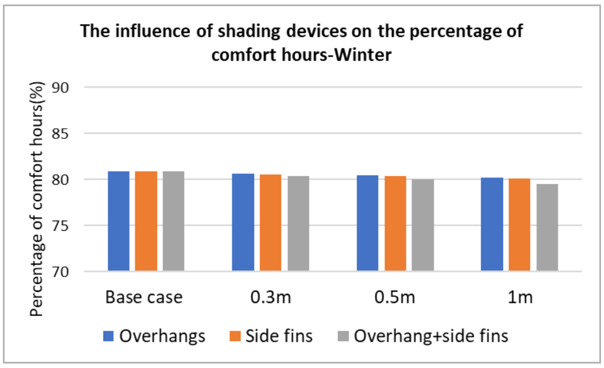


Figure 7. 61 Solar shading devices' influence on the percentage of comfort hours in summer and winter

Influence of Window Shading on Indoor Temperature in Summer and Winter

It can be clearly seen in Figure 7.62 that optimising the windows with surrounding shading at different projection depths has no influence on indoor temperatures during the summer or winter. This is attributed the limited solar gain through the windows due to the low window to wall ratio.

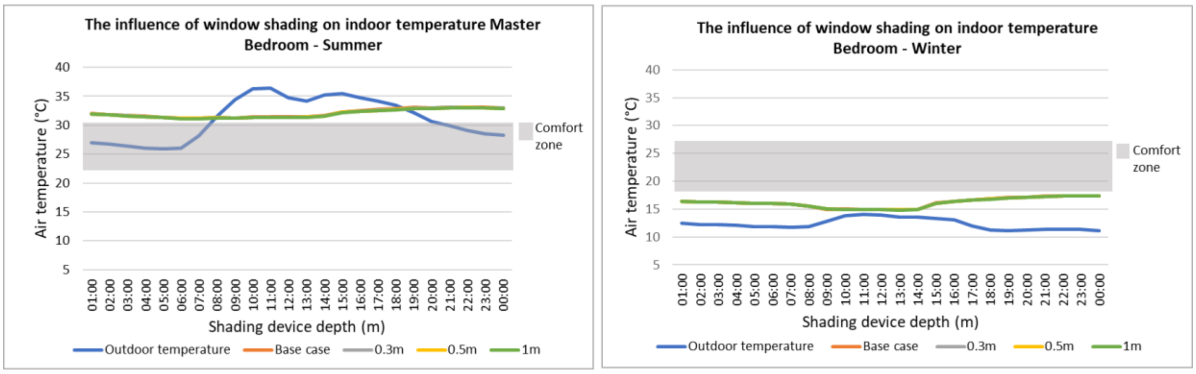


Figure 7. 62 Solar shading devices' influence on the percentage of comfort hours in summer and winter

7.3.3.2 Stage 2 Optimisation Results

A combination of moderate and extreme values for different parameters helps reduce the energy demand from 78111.28 kWh/y to 27798.6 kWh/y. The first simulation includes 1807 iterations of which the Pareto front produces 26 optimal solutions (Figure 7.63). The range of site energy consumption for the optimal solutions is from 32150.5 kWh/y to 27798.6 kWh/y, and none of the optimal solutions provided compromise in terms of thermal comfort. The second simulation includes 1783 iterations, of which the Pareto front produces 69 optimal solutions (Figure 7.64). The range of the site energy consumption for the optimal solutions was 32151.21 kWh/year to 27959.13 kWh/year. Accordingly, the position of the insulation material, whether internally or externally placed, does not substantially impact reduction in energy use. The most optimal design solution, producing the lowest energy consumption for the site, with an acceptable range of 84 % annual comfort hours at 64.41% energy reduction, includes the following design parameters:

- Roof with external insulation with a U-value of 0.1 W/m².K,
- Walls with external insulation with a U-value of 0.1 W/m².K,
- 'Trp Clr 3mm/13mm Arg' glazing with a U-value of 1.6 W/m².K and SHGC of 0.68.
- Side fins 0.5m +0.5 overhang for shading the NE windows, 0.3m overhang for the SE windows, side fins of 0.5m + a 0.5 overhang for shading the NW windows, and a 0.5 m overhang for shading the SW windows.

The optimal simulation that improved indoor thermal comfort to 84.6 % annual comfort hours at 58.8% energy reduction includes the following design parameters:

- Roof with external insulation with a U-value of 0.2 W/m².K,
- Walls with external insulation with a U-value of 0.2 W/m².K.
- 'Trp Clr 3mm/13mm Arg ' glazing with a U-value of 1.6W/m².K and SHGC of 0.68.
- A 1m overhang + 1m side fins for shading the NE windows, 0.5m overhang +0.5 side fins for shading the SE windows, 1m side fins for shading the NW windows, and a 0.3m overhang for shading the SW windows.

The primary energy consumption of the base case model is reduced from 179.54 kWh/m²/y to 115.26 kWh/m²/y, and the primary heating and cooling energy demand is reduced from 93.38 kWh/m²/y to achieving the Passivhaus retrofit target at 28.73 kWh/m²/y.

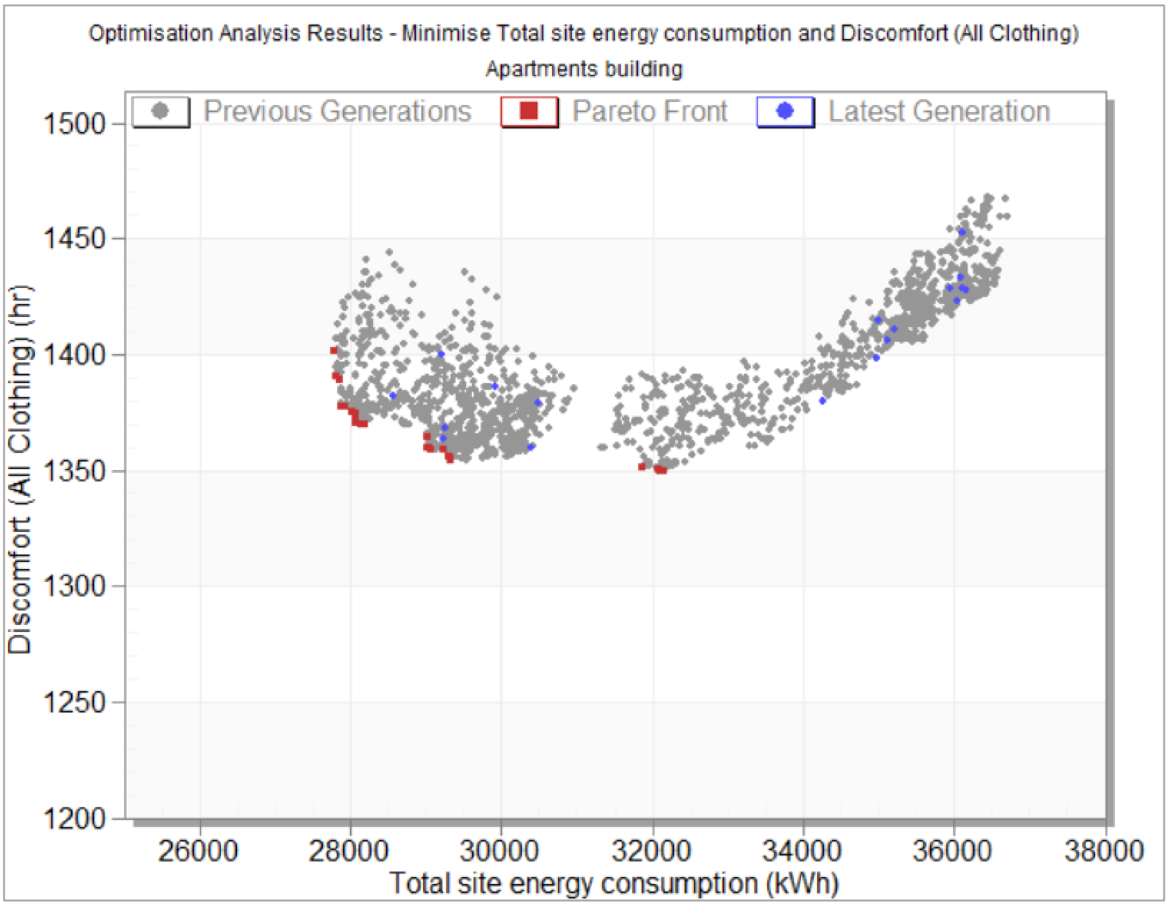


Figure 7. 63 Multi-objective optimisation result 1, Case Study 3.

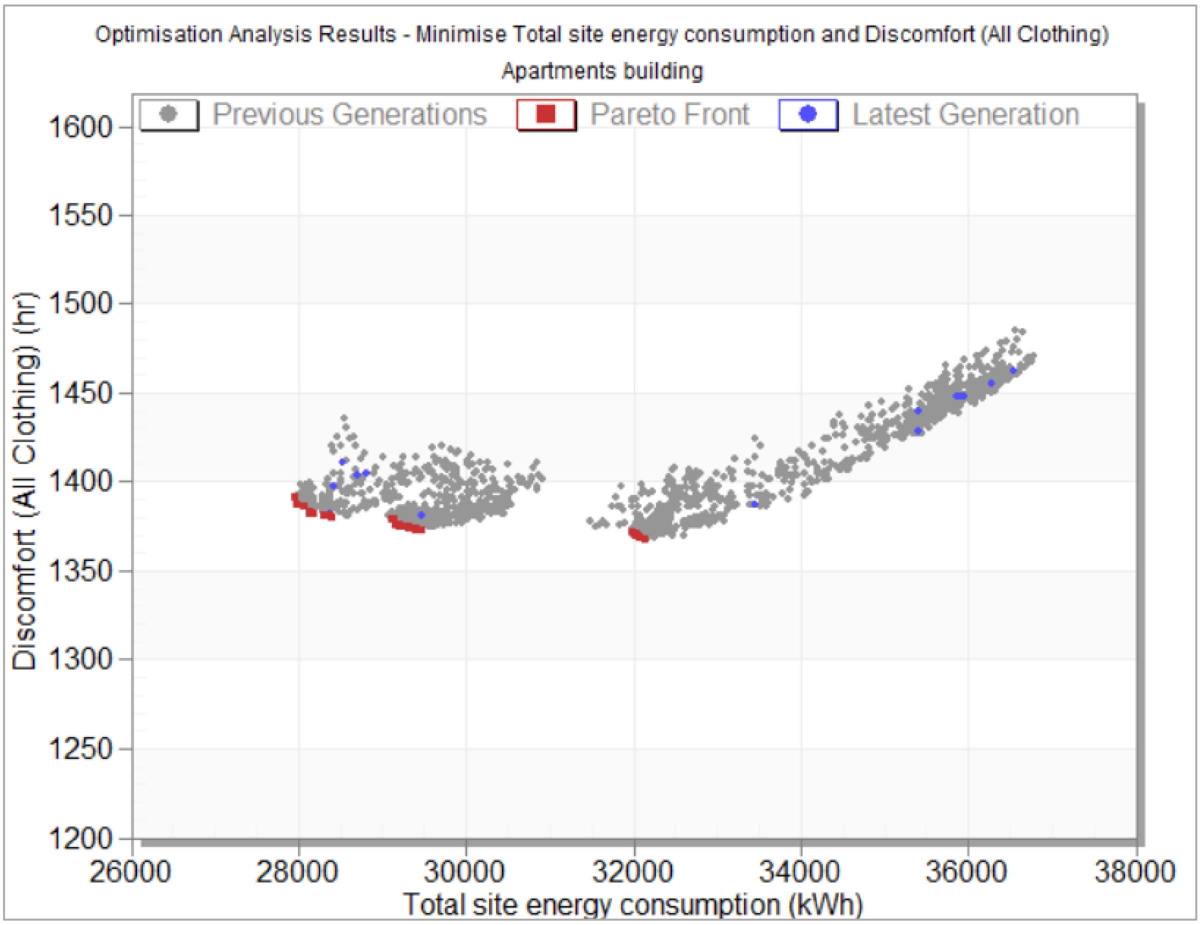


Figure 7. 64 multi-objective optimisation result 2, Case Study 3.

The Influence of Optimal Retrofit Solution on Indoor Temperature - Case Study 3

This section studies the influence of the optimal solution on indoor temperature in Case Study 3 during both summer and winter. As illustrated in Figure 7.65, the simulation results for the summer show that the optimal solution can achieve a noticeable reduction in indoor temperature, of between 2.3 °C and 3.7°C in the bedroom at wall and roof U-values of 0.5 W/m^2 K and 0.1 W/m^2 K, respectively, and bring indoor temperature to a comfortable level. Similarly in winter, a noticeable increase in indoor temperature is witnessed. For instance, the temperature in the bedroom is increased by 3.9 °C by the solution with wall and roof U-value of 0.5 W/m^2 K. The temperature is increased further by the optimal solution at a wall and roof U-value of 0.1 W/m^{2}K, to achieve a 6.2 °C increase in indoor temperature and bring indoor temperatures to a comfortable level.

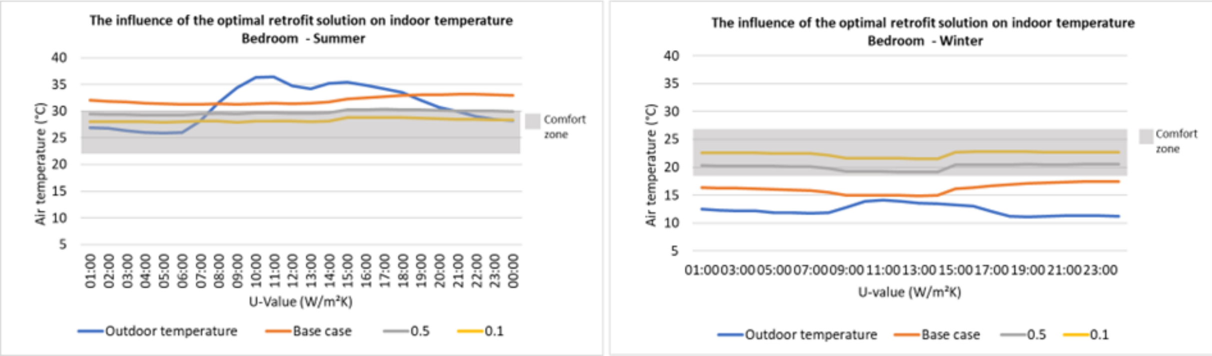


Figure 7. 65 The influence of the optimal retrofit solution on indoor temperature in summer and winter

7.3.3.2.1 Further optimisation scenarios

- **Further Energy Reduction through Adjusting Cooling and Heating Setpoints Based on the Acceptable Comfort Ranges of the ASHRAE Standard 55**

According to ASHRAE 55 standards, indoor thermal comfort in Libya ranges from 22°C to 30°C in the summer, and from 19°C-26°C in the winter. This means that people can feel comfortable at 26 °C in the summer and at 22°C in the winter. However, based on the building survey, the cooling set point is set at 22°C, while in winter, the heating set point is set at 23°C. As a result, if the set points of the base case model are adjusted based on the acceptable comfort ranges in summer and winter, greater energy reductions can be achieved.

To investigate this, the optimised Case Study 3 is further optimised by adjusting the cooling set point to 26 °C and the heating set point to 22 °C. The simulation results show that adjusting the cooling and heating set points in the optimised model achieves 14.38% additional site energy reductions. Primary energy consumption is reduced further from 115.26 kWh/m²/y to 105.45 kWh/m²/y, primary cooling and heating energy is reduced further from 28.73 kWh/m²/y to 18.93 kWh/m²/y, meeting the Passivhaus targets for retrofit.

- **Energy retrofit solution with roof and wall insulation only**

A passive retrofit solution that only incorporates roof and wall insulation at a U-value of 0.5 W/m²K achieves a 51.29% site energy reduction. Primary energy demand is reduced from 179.54 kWh/m²/y to 130.5 kWh/m²/y, while primary cooling and heating energy is reduced from 93.38 kWh/m²/y to 44.81 kWh/m²/y. At a roof and wall U-value of 0.1, a further energy reduction is achieved. The site energy consumption is reduced by 60.8%, primary energy demand is reduced from 179.54 kWh/m²/y to 117.1kWh/m²/y, while cooling and heating energy is reduced from 93.38 kWh/m²/y to 30.97 kWh/m²/y, meeting the Passivhaus retrofit targets.

- **Optimisation of the Base Case Study 1 Model as a Fully Conditioned Building.**

When optimising the base case model as a fully conditioned building using the optimal retrofit solution, it is found that primary energy consumption is reduced from 226.66 kWh/m²/y to 128.16 kWh/m²/y. The primary cooling and heating energy demand is reduced from 140.51kWh/m²/y to 42.28 kWh/m²/y. By adjusting cooling and heating set points based on the acceptable comfort range in Libya, additional energy reductions are achieved. The cooling set point is adjusted from 22 °C to 26 °C, and the heating set point is adjusted from 23 °C to 22 °C. The simulation results show that optimising the set points can achieve further energy reductions in which primary energy consumption is reduced to 109.73 kWh/m²/y, and primary cooling and heating energy is reduced to 23.21 kWh/m²/y, meeting the Passivhaus targets for retrofit.

7.3.3.3 Stage 3 Optimisation Results

This section explores the potential for meeting the requirements of net zero energy buildings for Case Study 3 by adding a photovoltaic performance model in DesignBuilder software. As mentioned in section 7.3.3.1, thermally renovating the building envelope could contribute to a 64.41% reduction in site energy consumption. To meet the remaining 35.59% of energy needs and achieve NZEBs targets, solar panels of 400W were installed on the roof. The simulation results show that the photovoltaic system consists of 37 solar panels of 400W arranged in five parallel lines with a total area of 74 m^2, meet the remaining energy needs and achieve net zero energy buildings requirements, considering that there remains enough space on the roof for an additional 19 panels, to supply the energy requirements of two additional storeys. Figure 7.66 shows the locations and areas for the installation of photovoltaic panels on the roof for Case Study 3. Table 7.4 shows a range of solutions, including the optimal solutions, the resultant energy conservation, and the number of solar panels required to achieve NZEBs targets for each solution.

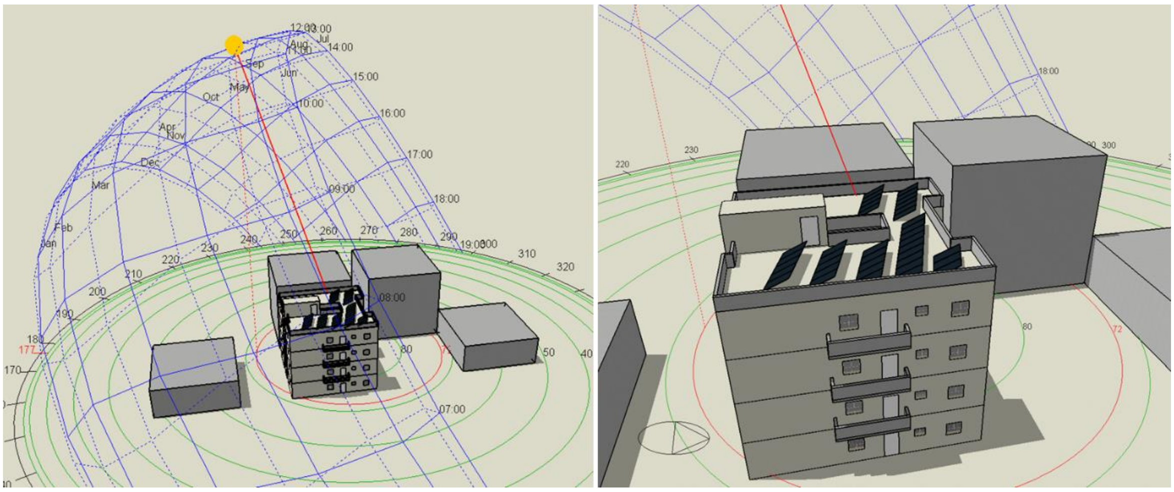


Figure 7. 66 Photovoltaic panel arrangement- Case Study 3

Table 7. 4 The optimal retrofit solutions and number of solar panels needed to meet NZEBs- Case Study 3

	Site energy consumption (kWh)	Percentage of comfort Hours (%)	Primary energy demand (kWh/m²/y)	Primary cooling and heating demand (kWh/m²/y)	U-Value (W/m²k) Wall; Roof	Saving %	Remaining energy need %	No. of Panels to NZEB
The optimal solution	27798.6	84 %	115.26	28.73	0.1; 0.1	64.41	35.59	37
The optimal solution with different wall and roof U-values	32766.05	84.3%	117.66	31.32	0.2 0.2	58.10	41.90	44
	34052.2	84.5	120.84	34.57	0.3;0.3	56.41	43.59	46
	35076.2	84.7	124.06	37.8	0.4;0.4	55.10	44.90	47
	36404.2	84.9	128.23	42.01	0.5;0.5	53.40	46.60	49
The optimal solution + adjusting the cooling and heating set points	23798.6	81.9	105.45	18.93	0.1; 0.1	69.54	30.46	32
	33796.5	80.1	119.05	32.84	0.5;0.5	56.73	43.26	45
Roof and wall insulation only	30605.7	83.1	117.1	30.97	0.1; 0.1	60.8%	39.20	41
	38042.2	82.9	130.5	44.81	0.5;0.5	51.29%	48.7	51

7.4 Final Discussion

In the light of the above results, it should be clear that the high U-value of the building envelope results in an increased rate of conduction heat gain and loss through the envelope, leading to the need for cooling in summer and heating in winter. Passivhaus retrofit standards require that all opaque surfaces of a building should have U-values of 0.5 W/m^2K or less (Passivhaus 2021). However, the U-values of the construction materials of existing residential buildings in Libya do not meet the U-value requirement of energy efficient building standards. The walls have a U-value of between 2.27 W/m^2K and 2.61 W/m^2K, while the roofs have a U-value of between 1.5 W/m^2K and 2.9 W/m^2K. The base case simulation results for the terraced house (Case Study 1) show that heat gain and loss by conduction through the roof and walls are the main contributors to the energy consumed for cooling and heating. However, the roof has a higher impact than the walls. This finding is consistent with a previous study by Alghoul et al. (Alghoul et al. 2018) who reveal that the roof in the terraced house is responsible for high thermal load. This is attributed to the fact that during the summer, solar heat gain from the horizontal surface (roof) is higher than that gained by vertical surfaces (walls). Another reason is that the roof receives the highest solar gain because it has the largest area exposed to solar radiation. In addition, the roof has a higher U-value than the wall, making it more conductive of heat. In the detached house model (Case Study 2) and apartment building model (Case Study 3), the walls are a major part of the building envelope and receive the highest amount of solar radiation. In addition, the walls have a higher U-value than the roof, making them more conductive of heat. Solar heat gain through windows makes less contribution to cooling and heating loads in all case study buildings compared to the opaque elements of the envelope. This is attributed to the low window-to-wall ratio (WWR), in which windows make up 15%, 20% and 10% of the surface in Case Studies 1, 2, and 3, respectively. Therefore, adding biobased insulation to the opaque elements of the building envelope has the highest impact on energy use reduction and improving indoor thermal comfort in each of the buildings studied. This finding is aligned with previous research which reveals that adding insulation to the building envelope has the greatest impact among a range of passive measures (Elaiab 2014; Alghoul et al. 2018; Ali 2018; Hamdani et al. 2021; Stasi et al. 2024). The ground floor in all case study buildings acts like a heat sink and adding insulation to it contributes to increased indoor temperatures in the summer, leading to increased cooling load. As a result, it is not recommended to insulate the floor, but rather to keep it uninsulated to utilise the thermal mass of the floor and help reduce cooling energy in the summer. This finding agrees with Sobhy et al.'s (2021) study, which finds that ground floor insulation is not required for buildings in a Mediterranean climate.

Optimising the roof with insulation materials

Reducing the U-value of the roof by adding biobased insulation to up to 0.1 W/m²K can reduce the cooling energy of the terraced house type (Case Study 1) by up to 25.7%, and reduces the heating load by up to 43.3%, respectively. Adding insulation to the roof also can achieve a decrease in indoor temperature in the unconditioned spaces by up to 3°C in the summer. In the detached house (Case Study 2), roof insulation achieves slightly less cooling and heating energy reduction compared to the terraced house type, where up to 35.6% and 33.6% reduction can be achieved, respectively. It also achieves up to 2.5 °C reduction in indoor temperature of the unconditioned spaces during the summer, and up to 1.7°C increase in indoor temperature during the winter. In the apartment building (Case Study 3), the roof is a minor part of the building envelope and receives a small amount of direct radiation. Consequently, roof insulation contributes to a minor influence on cooling and heating energy reduction. The cooling and heating energy can be reduced by up to 9.5% and 17.96%, respectively. Roof insulation also has a slight influence on indoor temperature where less than 1°C decrease can be achieved in the summer and less than 1°C increase can be achieved in the winter.

Optimising the walls with insulation materials

The external walls in the terraced house are a minor part of the building envelope and receives a small amount of direct radiation compared to the roof. As a result, its contribution to energy use reduction less than the roof. Reducing the U-value of the wall by adding biobased insulation to up to 0.1 W/m²K can reduce the cooling energy of the terraced house type (Case Study 1) to up to 21.4 % and reduces the heating load by up to 18.6%. However, insulating the external walls has no influence in indoor temperature in the unconditioned spaces. In the detached house (Case Study 2), the walls are a major part of the building envelope and receive the highest amount of solar radiation. Therefore, insulating the walls has great energy reduction potential, in which up to up to 44.84% and 29.15% reductions in cooling and heating energy can be achieved, respectively. Moreover, adding insulation to the external walls of the detached house also achieves up to a 1.3° C reduction in indoor temperature during the summer, while in the winter, no change in indoor temperature is achieved. Similarly, in the apartment building (Case Study 3), the walls are a major part of the building envelope and receive a large amount of direct radiation. Hence, wall insulation with biobased materials contributes a strong influence on cooling and heating energy reduction, in which cooling and heating energy can be reduced by up to 40.8% and 71%, respectively. In addition, wall insulation can contribute to a decrease in indoor temperature in summer of up to 1.4° C and an increase in indoor temperature of up to 2° C in the winter.

Optimising windows with energy efficient glazing.

Optimising windows with efficient glazing may have less impact than other measures on energy reduction. This is attributed to the limited solar gain through the windows due to the low window-to-wall ratio (WWR) with windows making up only 15%, 20% and 10% of the surface in Case Studies 1, 2, and 3, respectively. In the terraced house (Case Study 1), efficient glazing can achieve up to only 5%, and 1.6% reductions in cooling and heating energy, respectively. In the detached house (Case Study 2), the WWR is higher than that of the terraced house. As a result, efficient glazing has a higher impact on cooling and heating energy reduction, where up to 10.9%, and 2.4% reductions can be achieved in cooling and heating energy, respectively. In the apartment building (Case Study 3), where windows constitute only 10% of wall surfaces, efficient glazing has a minor influence on energy reduction, in which only up to 3.9% and 1.3% reductions in cooling and heating energy respectively can be achieved. These results support evidence from previous observations. A study by Ahn et al. (2016) reveals that in the case of a low window-to-wall ratio, the U-value and SHGC of energy-efficient glazing only has a slight influence on energy consumption. Regarding effects on indoor temperature, no influence can be achieved either during summer or winter with any of the types of efficient glazing in any of the case study buildings. In all case study buildings, reflective glazing achieves the highest reduction in cooling energy. However, it raises heating needs in winter. As a result, in the case of buildings with a high WWR, this option may not be appropriate. Based on the simulation results, triple LoE with argon filling (Tpr3), and triple clear glazing (Tpr2) are the best options to achieve a trade-off between cooling energy and heating energy reduction across each of the case study building types.

Optimising windows with local shading.

Similar to the effect of efficient window glazing, window shading has only a slight influence on cooling energy reduction across the case study buildings. This is also attributed to the low window-to-wall ratio, meaning that solar gain through the windows is limited. In addition, adding shading can has a reverse effect in the winter. Window shading reduces cooling energy by up to 6.5%, 12.4%, and 6.5% for Case Studies 1, 2, and 3 respectively, while increasing heating energy by up to 4.3%, 2.5% and 15.4% in Case Study 1, 2, and 3, respectively. However, because the reduction in cooling energy is greater than the increase in heating energy, and the level of thermal comfort in winter is not worsened by adding shading, solar shading can still be used.

The effect of combining different retrofit measures on building energy reduction

The combination of different passive retrofit measures has a considerable impact on energy reduction, in which up to 53.27%, 60.5 % and 64.41% reductions are achieved in Case Studies 1, 2, and 3, respectively. The combination of these measures helps in meeting or nearly meeting the Passivhaus retrofit target for primary energy demand and primary cooling and heating energy demand. Adjusting the cooling and heating set points in the optimised model achieves additional site energy reductions of up to 14.73%, 8.9% and 14.38% in Case Studies 1, 2, and 3, respectively. The combination of retrofit measures exerts a significant impact on improving indoor thermal conditions of the unconditioned spaces during the summer and winter. Combined retrofit measures can help reduce indoor temperature in the summer by up to 6.5 °C, 6.1°C and 3.7°C, and increase indoor temperature in unconditioned settings in the winter by up to 5°C, 3.4°C, and 6.2 °C in Case Studies 1, 2, and 3, respectively. These results are consistent with previous study results which show that adding insulation to the walls and roof can help reduce indoor temperatures by up to 6 °C in the summer (Elaiab 2014). They also agree with Hamadani et al.'s (2021) study, which reveals that adding insulation improves indoor thermal conditions, achieving indoor temperature reductions of up to 4°C. Retrofit solutions which only incorporate roof and wall insulation can also achieve notable energy reductions, of up to 45.96%, 58.68% and 60.81% respectively for Case Studies 1, 2, and 3. In addition to this, optimising the case study buildings and integrating a photovoltaic system of 400W on the roof helps in meeting remaining energy needs and achieving the target of NZEBs for all case study buildings.

7.5 Chapter Summary

This chapter started by presenting the calibrated base case simulation results. Heat gain and loss through the building envelope are identified as the main contributors to energy consumption in all three case study buildings. Accordingly, the case study building models are used to numerically evaluate the effects of upgrading the envelope parameters through the application of different retrofit measures. Passive retrofit measures include roof insulation, external wall insulation, ground floor insulation, an energy efficient glazing system, and window shading. With a view to reducing the embodied carbon associated with building retrofit, biobased materials including sheep's wall, camel hair, hemp fibres, and data palm fibres are employed in this study. The optimal combination of different retrofit measures achieves significant energy reductions with the potential to reach the Passivhaus target for retrofits. A further study is carried out on the optimised case study building models to explore the potential for meeting remaining energy needs with solar PV systems. The results demonstrate that the target of NZEBs can be attained for each of the case study buildings.

Chapter 8: Conclusion and Recommendations For Future Work

8.1 Introduction

This chapter presents an overview of this research work and its implications, based upon fulfilling the research aim and objectives. The chapter forms a synthesis of the research findings from the literature review, and research work conducted to inform optimal design solutions to retrofit existing residential buildings as well as designing energy efficient dwellings for the future. It summarises the various contributions to knowledge and considers how the research has bridged the identified research gaps. The chapter also addresses the research limitations and areas for future study.

8.2 Research Summary

Concerns about climate change and global warming have become increasingly prevalent over the past few decades. The building and construction sectors are the main contributors to a significant percentage of the world's energy consumption and energy-related CO_2 emissions. Therefore, there should be a global effort towards reducing the energy consumption of this sector, not only by designing energy-efficient buildings for the future but most importantly by improving the energy efficiency of existing buildings especially because existing buildings constitute a significant percentage of the total number of buildings that are expected to remain in the future. Energy use in existing residential buildings in Libya is also found to constitute 36% of energy demand, with these dwellings having been built without considering thermal and energy conservation requirements. As a result, energy efficiency in existing residential buildings is now an urgent priority for Libya's energy policy, not only to save the environment and the national economy but also to promote the Libyan contribution to the global efforts to combat climate change and move toward a sustainable environment. This research comes as a step toward achieving this target. A review of the literature was conducted to explore the current knowledge in the research field of energy efficiency in residential buildings, with a particular focus on the Libyan context. It was found that there is limited research conducted on improving the energy efficiency of residential buildings in Libya, with only one published study being found. Consequently, the novelty of this research lies in identifying the optimal solutions for retrofitting different residential building types in Libya to meet the net zero energy target. Although the study area of this research is Benghazi, the research recommendations can be applied to many other cities in Libya that share a similar weather profile and architectural features.

Based on the literature review, thermally renovating residential buildings in Mediterranean countries by upgrading the building envelope with insulation materials and upgrading the windows with energy-efficient glazing and shading showed the highest impact in energy use reduction compared with other retrofit measures. However, to meet the net zero energy target, the integration of renewable energy into retrofit measures was required. In addition, solar energy has shown its effectiveness in generating energy for residential buildings in Mediterranean countries, where it has been incorporated into all research aimed at reaching net zero energy levels. Therefore, a hybrid optimisation approach that combines passive retrofit measure and on-site PV energy generation is adopted in this research to meet the net zero energy target for Libyan housing stock.

Embodied carbon reduction in building retrofits is a topic which deserves full consideration. Biobased insulation materials, for example, are renewable and contribute to reducing the embodied carbon of the building. However, most previous research, including that in the Libyan context, has deployed petroleum-based insulation materials, and only three research works have investigated biobased insulation materials. Accordingly, this research investigated the effectiveness of different biobased insulation materials on energy reduction in Libyan housing stock. This provides an additional contribution to existing knowledge.

A major weakness is represented in the credibility of the energy models applied in the majority of studies reviewed, including that on Libyan houses, as these studies were carried out without ensuring the reliability of the energy model. Thus, for robust model calibration, ensuring that the building model represents actual building performance, and for reliable optimisation of simulation results, annual building energy and environmental measurement in three different Libyan housing stocks were carried out to collect actual data for model setting and calibration. The building energy models were calibrated on a monthly and hourly basis as defined by ASHRAE 14-2002 calibration criteria to ensure the reliability of the simulation study results.

This research aimed to identify the optimal solutions for retrofitting existing residential building stock in Libya to meet the net zero energy buildings target by proposing a hybrid retrofit approach. To fulfil the aim of the study, four objectives were formed to accomplish sequential tasks:

1- **To select representative buildings from different residential building typologies in Benghazi to investigate building energy retrofit measures.**

The research included an overview of the national housing typology with a focus on Benghazi, to understand the key features of the housing stock and justify selection of particular residential building types for the study. The review initially sought to identify the dominant residential types, which consequently have significant potential for energy saving. Based on the review results, there are three key residential building types namely terraced houses, detached houses, and apartment buildings. However, because all existing residential dwellings are below sustainability criteria, all three types were included in this study. The selected case study buildings represent the existing residential building types in terms of construction materials, floor area, number of occupants, and occupant lifestyle.

2- To identify the key contributors to energy consumption in existing residential buildings in Benghazi, Libya.

To accomplish this objective, three case study buildings were surveyed and monitored to collect the data required for generating and calibrating the building model. A weather station was used for one year to collect data on outdoor weather variables. The data collected was used to create an Energy Plus Weather (EPW) file, which was used as input data. Indoor temperature data was measured for three months: a month in the summer; a month in the winter; and a month in a transition season, and then used to calibrate the building models. Energy consumption was measured for one year to determine which category consumed energy the most. The data was also employed for model calibration. Heat flux through the walls was measured to determine U-values, which were used as input data for model generation in DesignBuilder.

Based on the monitored data, the case study buildings consume the most energy for cooling in summer and heating in the winter. Accordingly, cooling load and heating load were set as objective functions for the sensitivity analysis which was used to determine the hierarchical order of the sensitive parameters. Once these parameters had been determined, the most influential parameters were tuned manually until an acceptable discrepancy between the measured and simulated data was achieved. The discrepancy between measured and simulated data on energy consumption and indoor zone temperatures was calculated based on ASHRAE Guideline 14-2002, using two statistical indices: normalised mean bias error; and coefficient of variation of the root mean squared error, and both hourly and monthly calibration approaches were adopted in this study.

Based on heat balance simulation results for summer and winter, the building envelope parameters, including the external walls, roofs, and windows in all case study buildings, are responsible for building heat gain and loss. Internal heat gain was limited compared to that through the building envelope. As a result, optimising the envelope parameters formed the main measures for thermally retrofitting the existing residential stock.

3. To analyse the effect of single and combined retrofit measures on energy and thermal performance during the heating and cooling seasons, to determine the optimal energy retrofit scenario for reducing energy consumption without compromising thermal comfort in existing residential buildings of Benghazi, Libya.

The calibrated simulation models developed in DesignBuilder were used to evaluate the effects of optimising building envelope parameters for energy consumption and thermal comfort. The first stage of the optimisation approach was to assess the influence of each parameter individually, to identify which had the highest impact on the energy consumption of the buildings. Single retrofit measures showed that for the terraced house type (Case Study 1), insulating the roof had the highest impact on reducing energy consumption, while for detached houses (Case Study 2) and apartment buildings (Case Study 3), the walls had the highest impact on energy consumption. Glazing and shading showed low influence on energy consumption compared to the roof and walls in all case study buildings. In addition, insulating the ground floor is not recommended due to its significant contribution to increasing cooling load in summer.

In considering how to improve performance a combination of these measures was assessed. The multi objective optimisation simulation results showed a significant improvement in the overall performance of the three case study buildings where the combined retrofit measures cut down the site energy consumption of all case study buildings by more than half. In addition, the results show that a combination of these measures helps in meeting or nearlly meeting the Passivhaus target for retrofits with regard to primary energy demand and primary cooling and heating energy demand.

4. To investigate the potential for using a renewable energy source to achieve the requirements of net zero energy buildings

Following the building optimisation stages using passive design principles, a further investigation was carried out to investigate the effectiveness of integrating a PV system to meet the remaining buildings energy demand. A geometric model for a photovoltaic system of 400W was generated on the roof of each building model. The photovoltaic electrical performance model was created within DesignBuilder, using actual manufacturer’s specifications. The outcome demonstrates that the photovoltaic system added to the roof of each case study building can meet the remaining 46.7%, 39.5% and 35.59% energy needs of the case studies 1, 2, and 3 respectively. Therefore, based on the optimisation simulation results, the existing residential buildings in Benghazi could attain the status of NZEBs were they to be retrofitted using a combination of passive retrofit measure and on-site PV energy generation system.

8.3 Research Contributions to The Body of Knowledge

This study is the first of its kind to develop a solution for retrofitting existing residential buildings in Benghazi, Libya to meet net zero buildings energy targets. Although the study area of this research is the city of Benghazi, the research recommendations can be applied to many other cities in Libya, as they share a similar weather profile and architectural features. The study outcomes reveal several contributions to knowledge in the field of buildings energy retrofit for the climate of Libya. These key contributions are presented under the headings of theoretical, policy, social, economic, and environmental contributions.

8.3.1 Theoretical Contributions

The primary contribution to knowledge is in identifying optimal solutions for achieving energy efficiency in existing residential buildings in Benghazi city. The approach combines passive retrofit measures and the integration of renewable energy measures to meet net zero energy buildings targets.

Another contribution of this research is in assessing the effect of different biobased insulation materials in improving the energy efficiency of existing residential buildings in Benghazi, including sheep's wool, camel hair, date palm, and hemp fibre. Camel hair insulation was first tested and thermally characterised in this research, which can be considered another novel contribution. Biobased insulation materials are renewable and low-carbon and contribute to reducing the embodied carbon of the building when compared to using petroleum-based insulation materials.

The methods and approaches illustrated in this study relate to net zero energy retrofitting and can be adopted by others to assess and optimise buildings within the Libyan context. The research illustrates in detail the process by which different retrofit measures were simulated and analysed towards achieving an optimal retrofit approach to meet the net zero energy buildings target. Professionals such as engineers, architects, environmentalists and policymakers can adapt or build upon these methods of research for future studies.

8.3.2 Policy Level and Practical Contributions

The approach proposed can be used as a tool for underpinning building regulations regarding retrofitting residential buildings in Libya. This will encourage the Libyan government to implement an energy efficiency programme for retrofitting existing residential stock, which will in turn provide economic and environmental benefit to the country, as well as job opportunities. In addition, the outcomes of this research will also guide architects in implementing Passivhaus strategies into their designs, enhancing capacity to achieve energy efficient buildings for Libya. and contributing towards achieving net zero energy buildings targets for Libya's housing stock.

The data gathered and documented in this research provides relevant information and data on the Libyan residential building industry, climate, building materials, thermal properties of the building envelope, and breakdown of building energy use. These data can be utilised by policymakers for the formulation and execution of policies on energy efficiency in the Libyan built environment.

8.3.3 Environmental and Economic Contributions

Buildings optimisation, based on this research, has considerable scope for reduction of the energy consumption of buildings, thereby potentially reducing operational CO_2 emissions. Therefore, the adoption of the recommended passive retrofit measures and renewable energy sources will cut CO_2 emissions within the Libyan residential building stock, which is expected to increase in the coming years.

Comparison of the optimised buildings' energy performance using passive retrofit measures against global building energy standards reveals that the total energy consumption of the optimised case study buildings can meet the targets of Passivhaus for retrofit. Integrating passive retrofit measures and active renewable systems within the retrofit approach can improve the energy efficiency of Libyan housing stock to meet the target of net zero energy buildings. Moreover, this research recommends the use of biobased insulation materials instead of petroleum-based insulation materials, as they require less energy to manufacture, and can sequester carbon during their growth, leading to embodied carbon reductions. Therefore, the retrofit solutions based on this research will decrease building energy consumption and operational and embodied CO_2 emissions.

The proposed retrofitting approach will encourage the construction industry in Libya to manufacture biobased insulation materials: especially considering the availability of raw materials in the country. In addition, Libya has a high solar energy potential, and the photovoltaic systems integrated within the retrofit approach showed promising results meaning that the prospect of meeting the NZEBs target is in view for Libyan housing stock. This will encourage the production of PV panels in Libya, which will contribute to the local low-carbon economy.

8.3.4 Social Contributions

Libyans suffer from frequent blackouts as a result of the growing demand for energy to maintain comfortable conditions, and particularly in the summer and winter. Retrofitting existing residential buildings can not only improve building energy efficiency but also allow the buildings to be more thermally comfortable, leading to enhanced living conditions for the occupants.

8.4 Research Limitations

There are specific limitations associated with this study. Those limitations are outlined below:

1-There are limited studies on energy efficiency for Libyan buildings. Therefore, it was difficult to find current studies in the research context.

2-This research approach focuses on the climate of northern Libya, which, while representing the climate of many other Libyan cities, may not be suitable for predicting the impact of energy retrofitting in mountain and desert climates.

3- The approach taken in this study is limited to existing residential buildings. Therefore, the study results may not be suitable for application to improve the energy performance of other types of building.

8.5 Suggested Areas for Future Research

The following study directions related to this study may benefit from further investigation:

1-This research has identified several optimal retrofit solutions for reducing energy and improving thermal comfort. Therefore, it would be useful to conduct a study in the future to prioritise these based on their economic feasibility. This type of study would help avoid economic hurdles that may prevent the adoption of net-zero regulations.

2-Net zero energy regulations address embodied and operational CO_2 emissions. Therefore, further research is required to quantify the environmental impact of the retrofit solutions through the buildings' life cycle. This will help in retrofitting buildings with low carbon footprints and achieving net zero goals in the Libyan context.

3-Developing strategies for the standardisation of housing types and building elements for more sustainable construction. Using similar building elements can enhance the reusability of elements in buildings. Hence, future studies are needed to develop strategies for the standardisation of housing types, building elements, and materials in the Libyan context. These strategies will lead to faster construction times, lower costs, and a reduction in the overall carbon footprint.

4-The existing residential buildings do not meet the occupants' privacy and social needs, and all family activities have moved inside the house, resulting in higher levels of energy consumption. Hence, it would be beneficial for future research to provide guidance for designing residential buildings that align with the occupants' social activities. This would reduce the need for energy.

5 -Applying the research methods adapted in this research to assess and improve the energy efficiency of residential buildings in other Libyan climates, such as mountain and desert climates, and to improve energy efficiency for other types of buildings, such as educational and healthcare buildings.

Publications From This Research

2025

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Appendices

Appendix A: Setting up The Monitoring Devices

A1.1 Tempo Disc™ 4 in 1

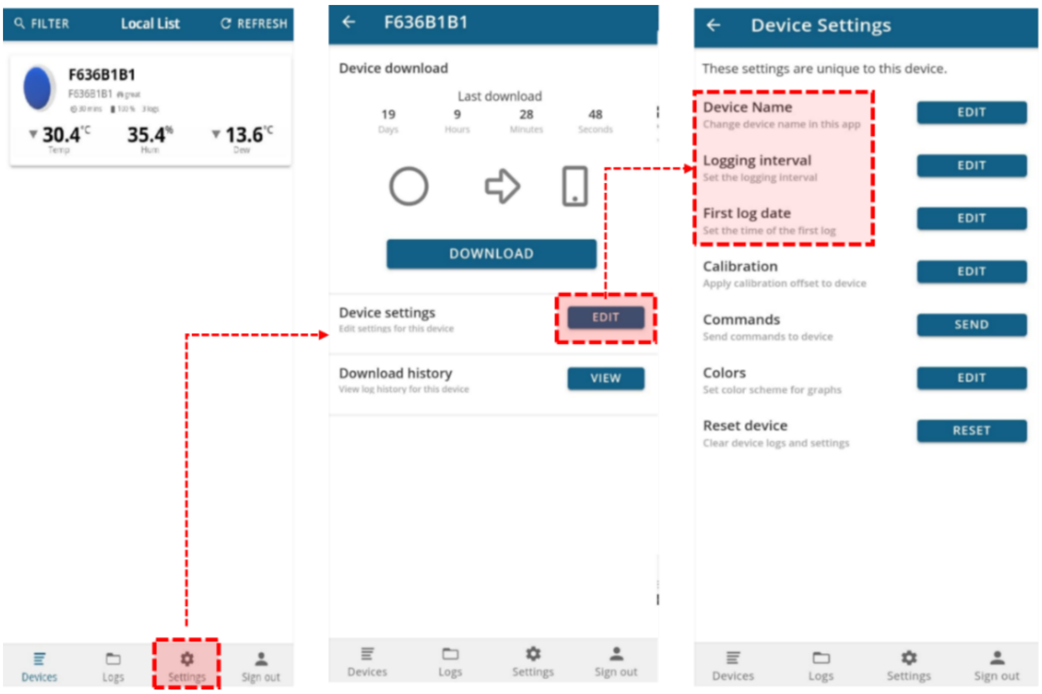


Figure A1.1 Bluetooth Sensor Logger setting using tempo plus 2

Figure A1.2 Readout and export the data

A1.2 Weather station

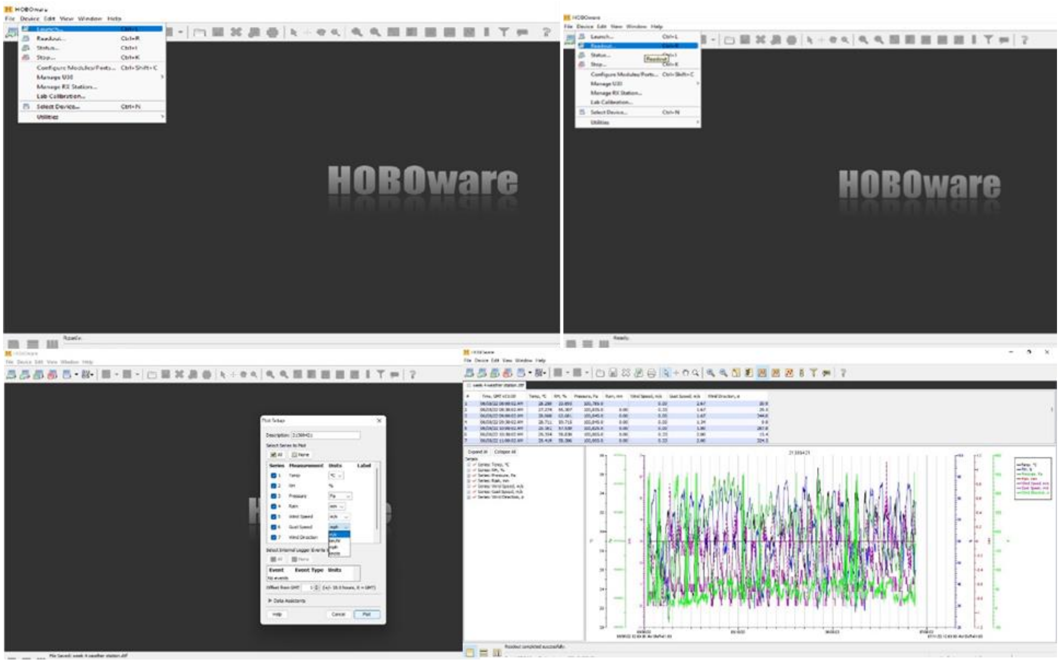


Figure A1.3 Weather station setting up

Annual Weather data

Outdoor temperature

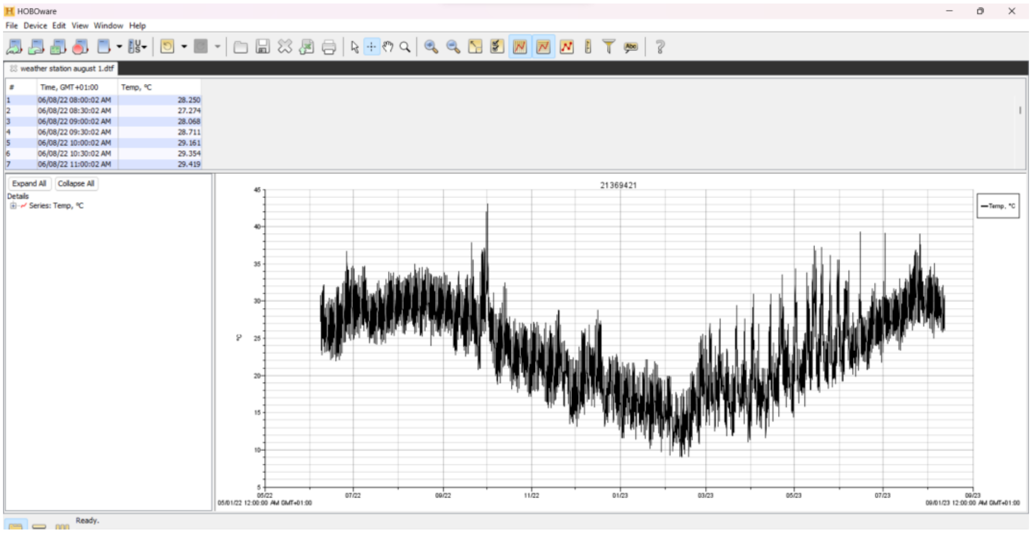


Figure A1.4 Outdoor temperature data between June 2022- August 2023

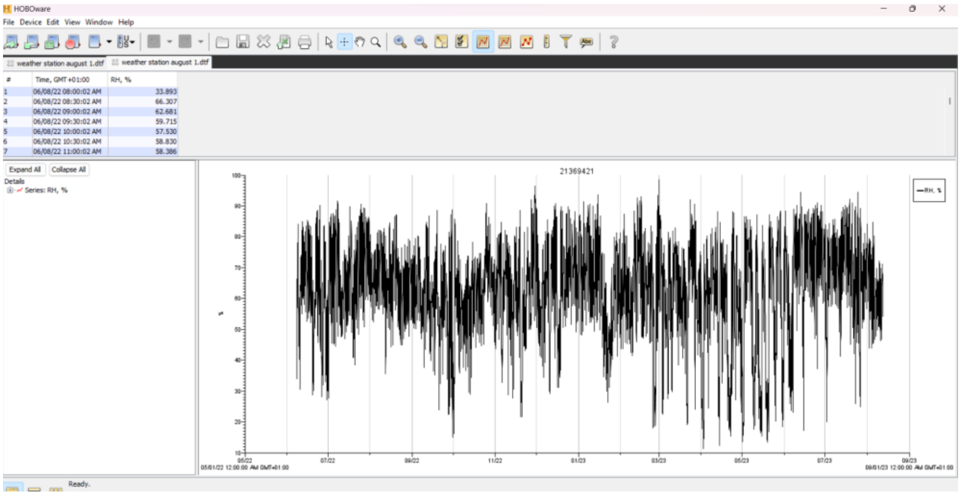


Figure A1.5 Outdoor relative humidity is data between June 2022- August 2023

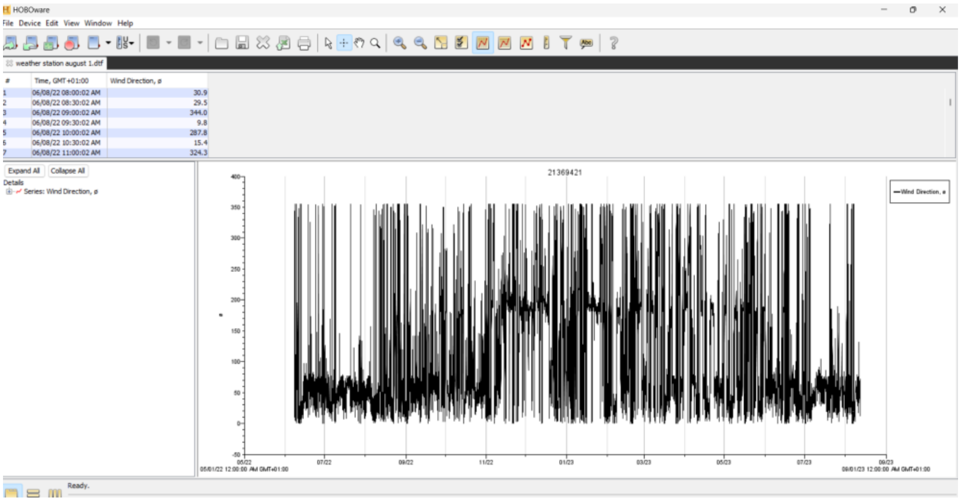


Figure A1.6 Wind direction data between June 2022- August 2023

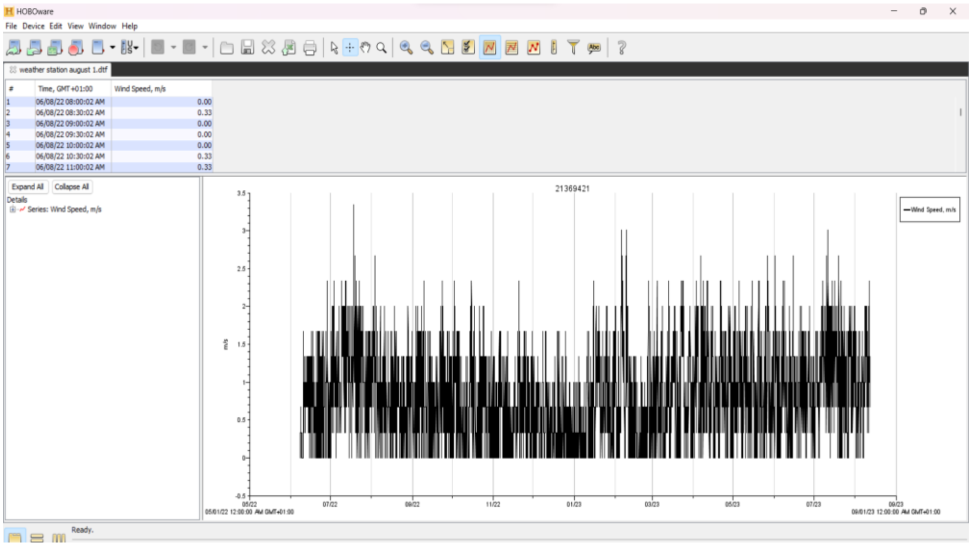


Figure A1.7 Wind speed data between June 2022- August 2023

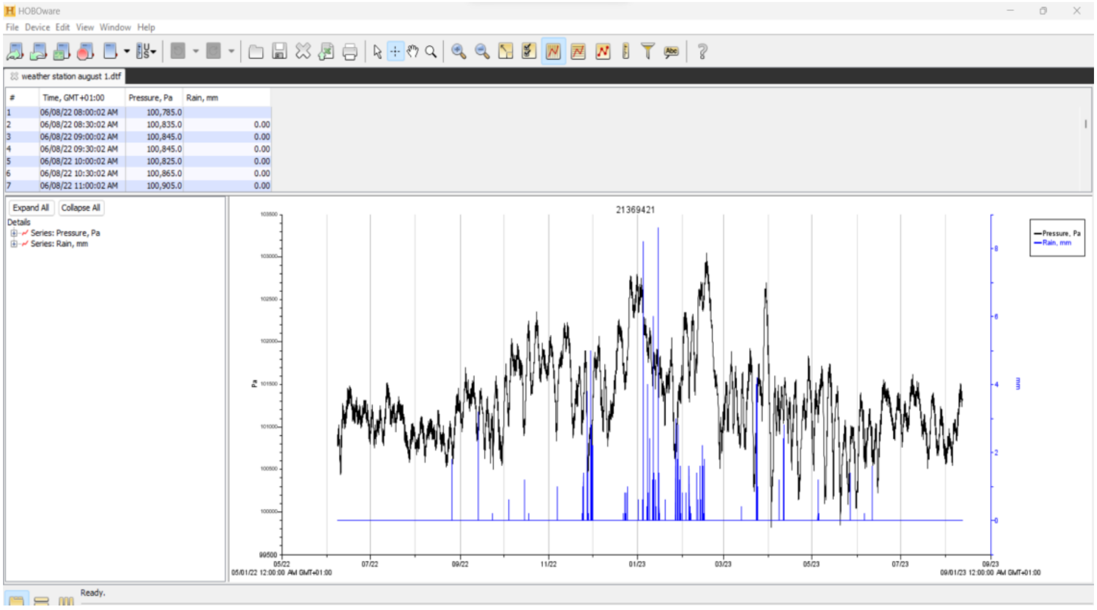


Figure A1.8 Rain and air pressure data between June 2022- August 2023

A1.3 GreenTEG heat flux sensor

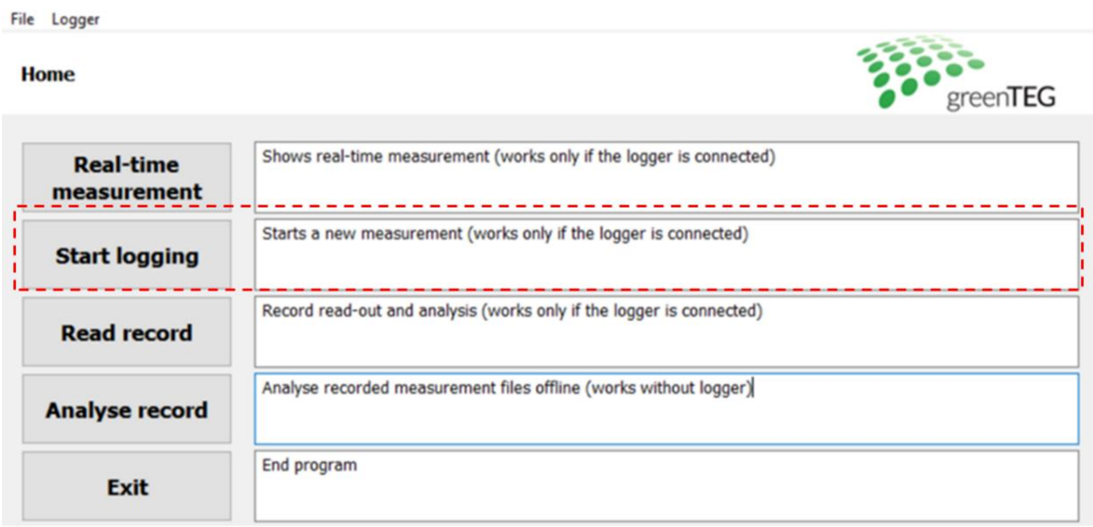


Figure A1.9 Setting up the GreenTEG heat flux sensor

A2: Monitoring equipment installation

A2.1 Tinytag clamp meter

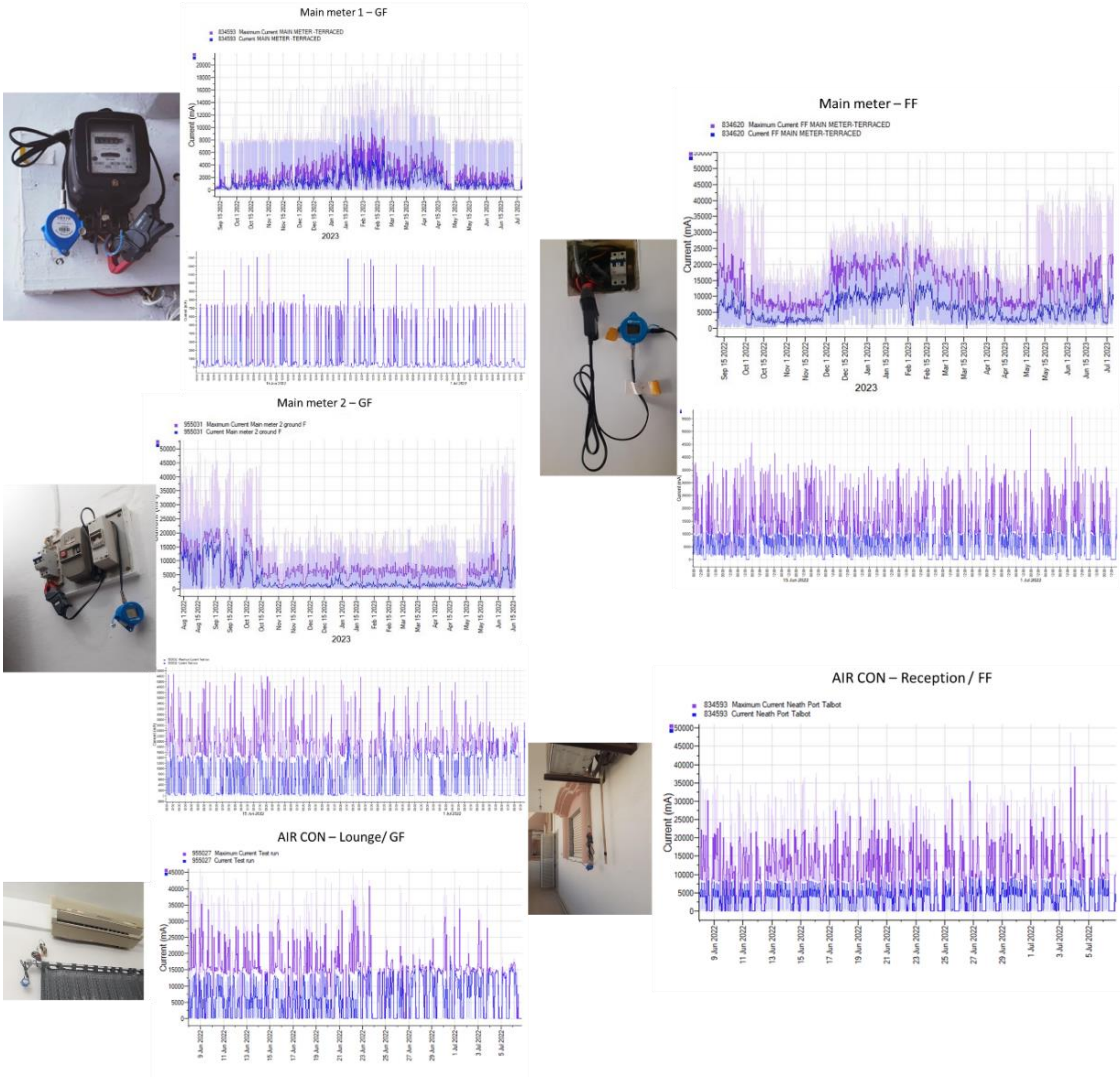


Figure A2.1 Installation of the tinytag clamp meters on the main meters and AC units – Case Study 1

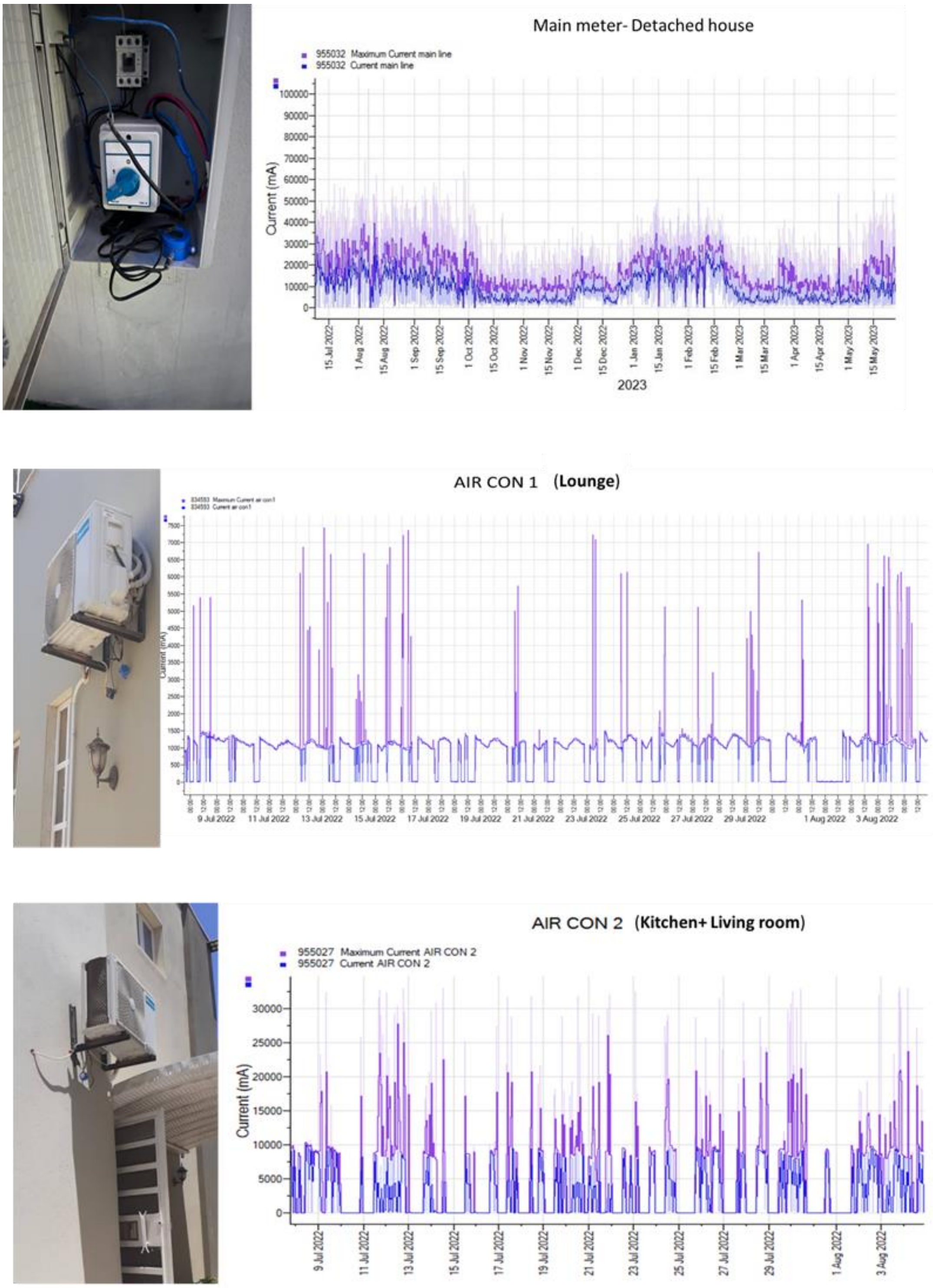


Figure A2.2 Installation of the tinytag clamp meter on the main meter and AC units – Case Study 2

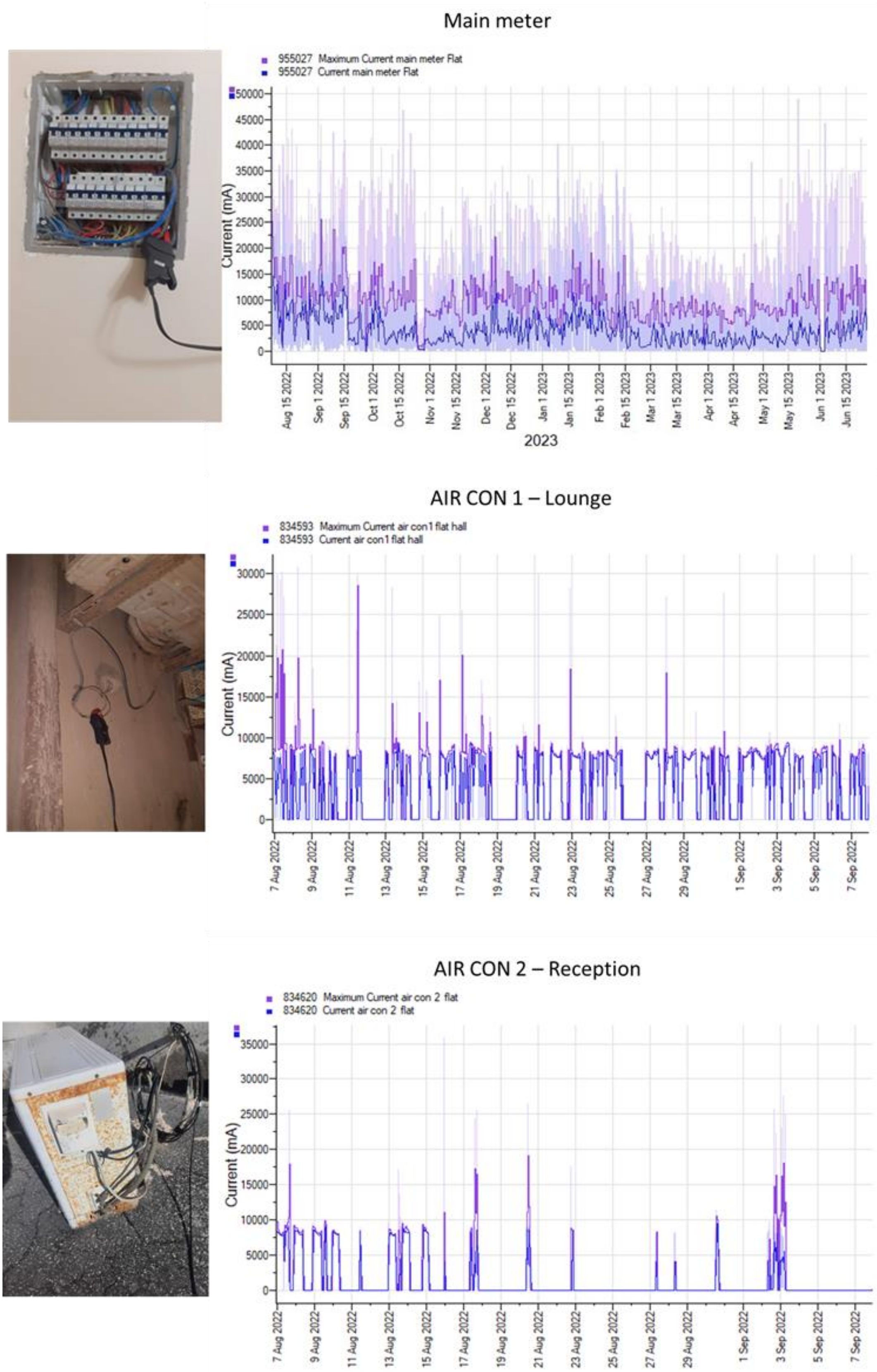


Figure A2.3 Installation of the tinytag clamp meter on the main meter and AC units – Case Study 2

A2.2 Sockets energy meters

Figure A2.4 Electrical heaters energy consumption measurement for Case Study 1

Figure A2.5 Electrical heaters energy consumption measurement for Case Study 2

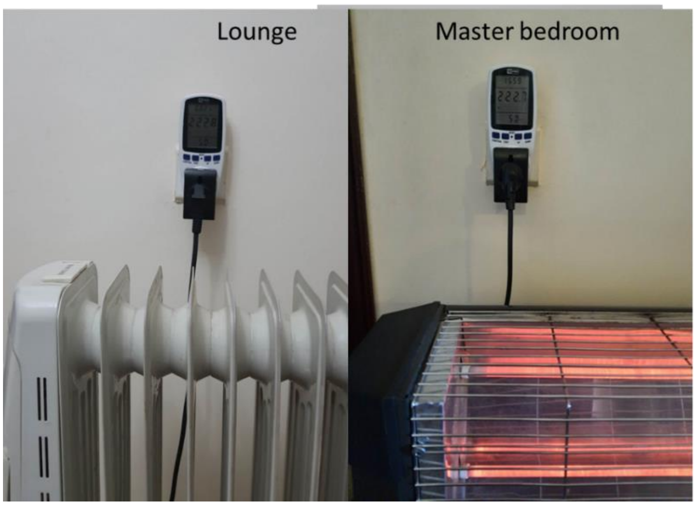


Figure A2.6 Electrical heaters energy consumption measurement for Case Study 3

Appendix B: Building Information and Occupancy Schedule

B1: Occupancy schedule setting in DesignBuilder

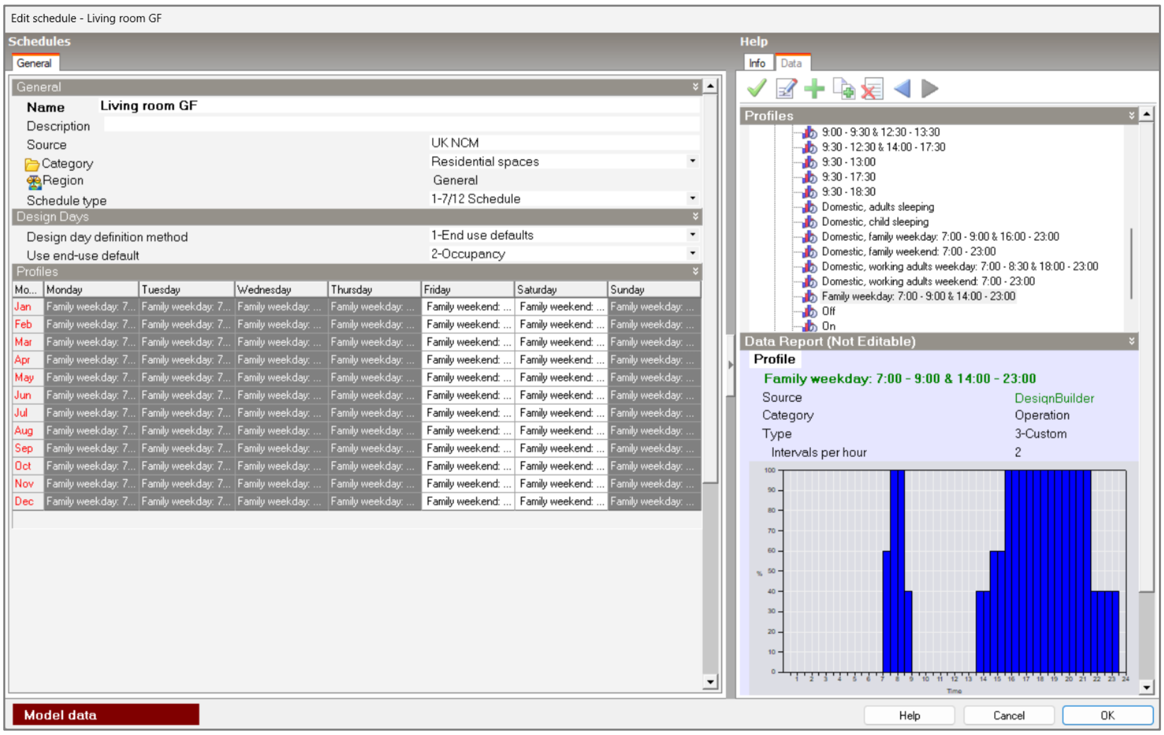


Figure B1.1 Occupancy Schedule of the living room GF-Weekdays

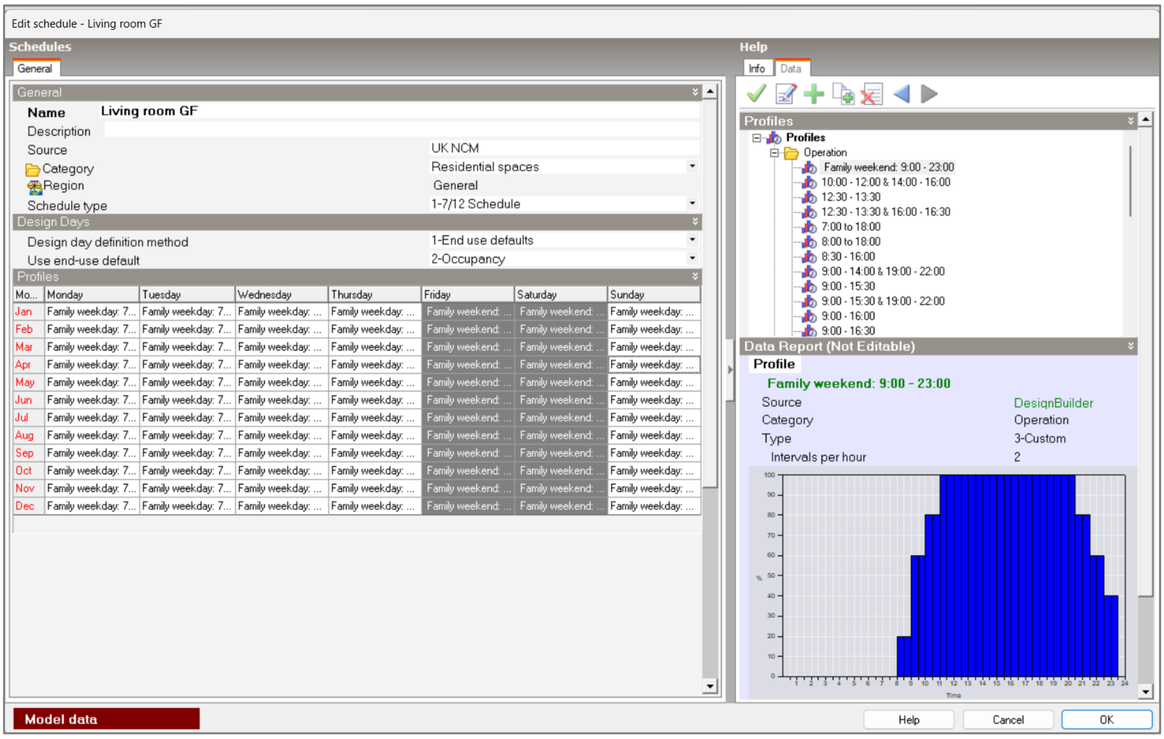


Figure B1.2 Occupancy Schedule of the living room GF-Weekend

B2: Materials information Setting in DesignBuilder

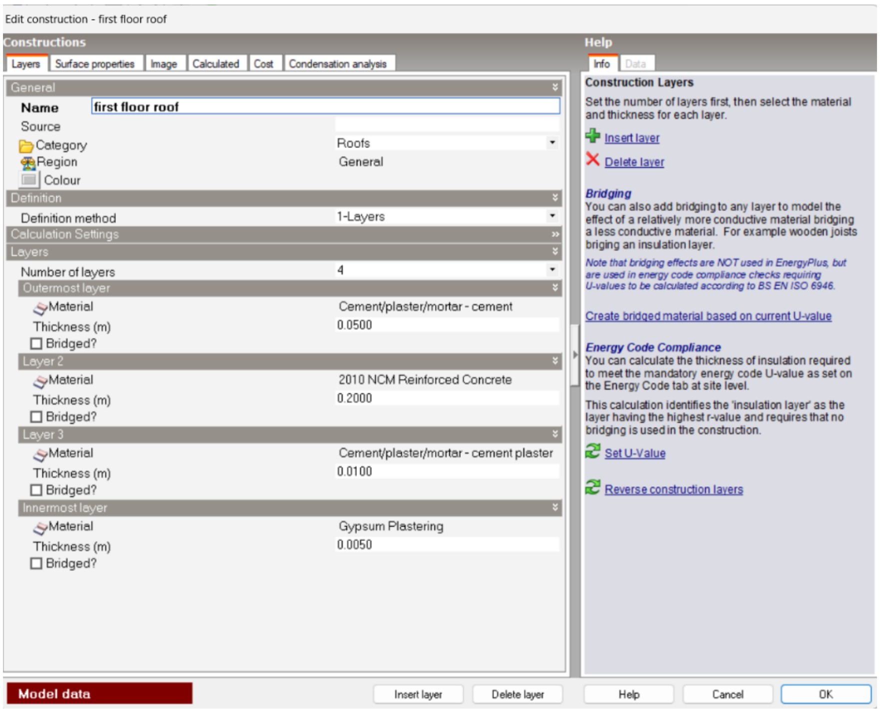


Figure B2.1 Roof materials setting in DesignBuilder-Case Study 1

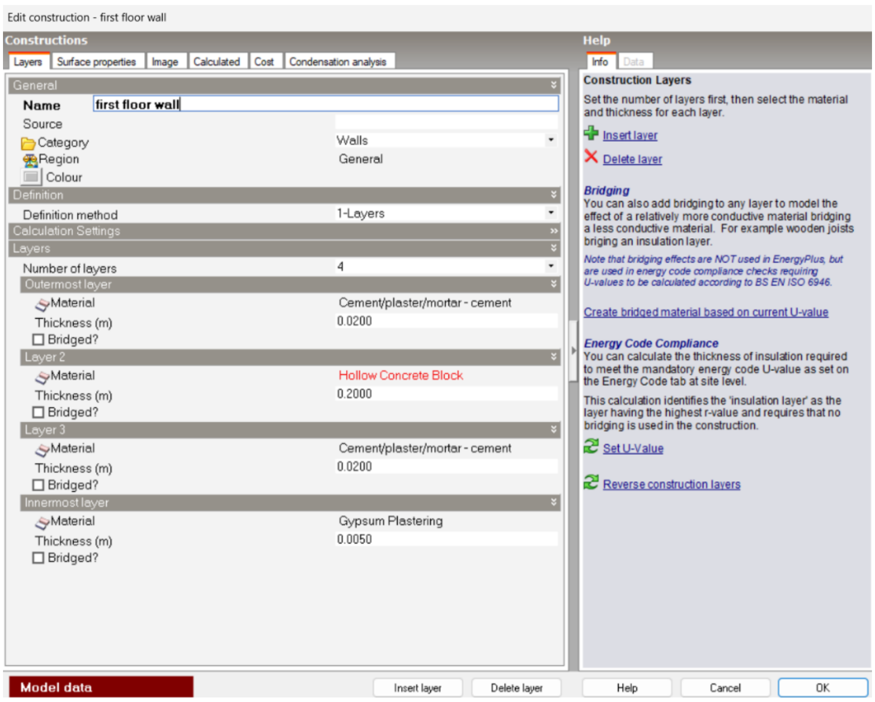


Figure B2.2 First floor wall materials setting in DesignBuilder-Case Study 1

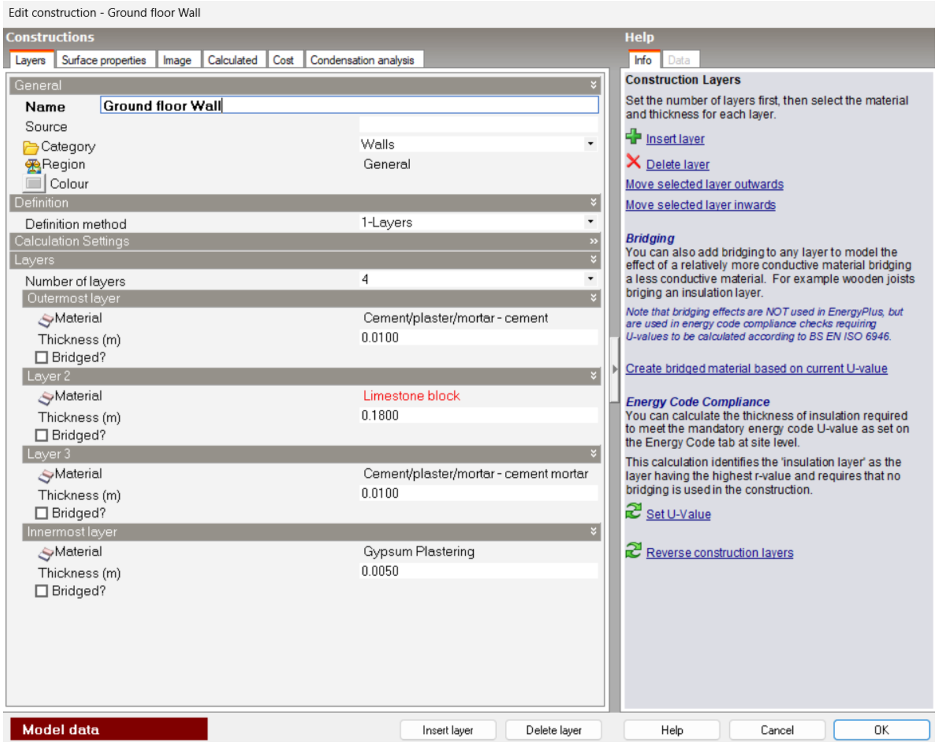


Figure B2.3 Ground floor wall materials setting in DesignBuilder- Case Study 1

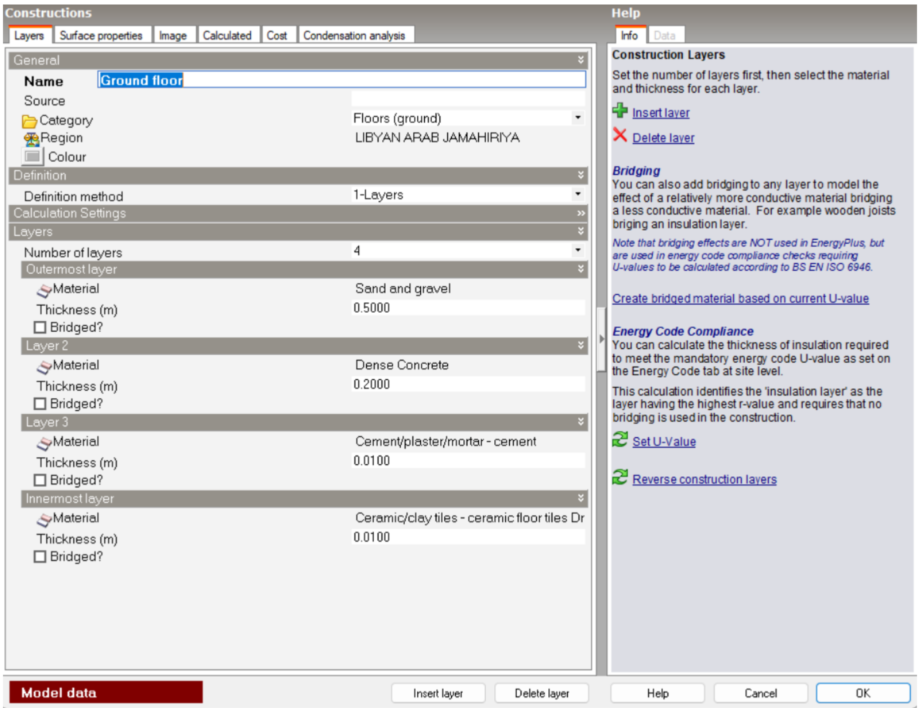


Figure B2.4 Ground floor foundation materials setting in DesignBuilder-Case Study 1

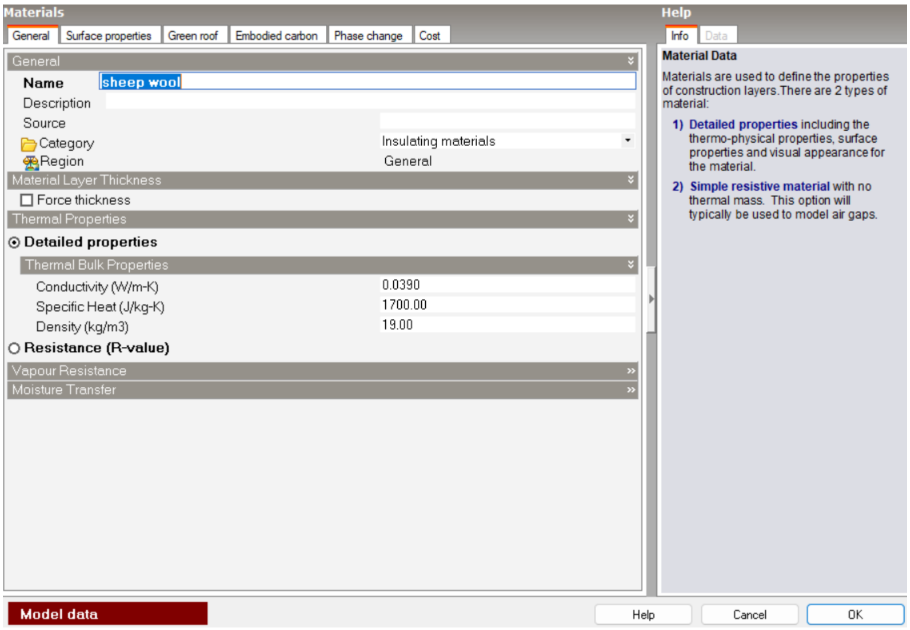


Figure B2.5 Sheep wool insulation material setting in DesignBuilder-Case Study 1

Appendix C: Heat Flux Measurement Results for Hollow Concrete Block Wall, and Limestone Block Wall.

greenTEG

Measurement result:

Logger data:

Serial No:	331053		
Type:	U-value measurement kit	Inside temp. (T1):	26.4 °C
Sensitivity:	10.7 uV/(W/m²)	Outside temp. (T2):	26.6 °C
Config.:	CB125BA	Measurement time (t):	317.50 h

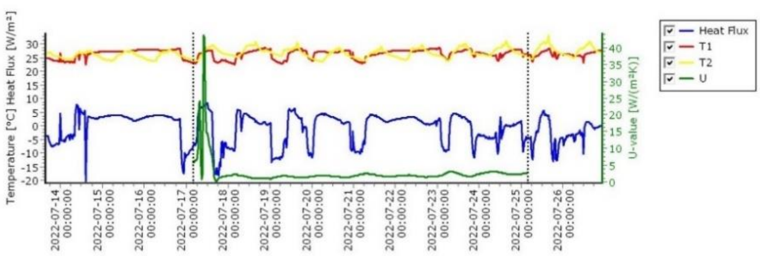
U-value analysis using average method (Section 7.1, ISO 9869-1:2014):

Analysis start time:	2022-07-17 04:10:52	U-value w/o last 24h (U24):	2.67 W/(m²K)
Analysis end time:	2022-07-25 04:10:52	U-value first 2/3 (U2/3):	1.82 W/(m²K)
Analysis period:	192 h	U-value last 2/3 (U2/3):	1.83 W/(m²K)
U-value:	2.61 W/(m²K)	dU24:	-1.9 %
		dU2/3:	-0.6 %
		dR24:	3.5 %
		dR2/3:	0.9 %

Measurement data fulfils requirements of ISO 9869-1:2014 section 7.1.
Uncertainties due to improper installation or environmental influences must be estimated by user (see section 6.1).

Additional comments:

Measurement overview over t=317.50 h



This report has been generated by greenTEG U-value Software v1.02.10 (2022-07-26 22:10:14)

Figure C1.1 U-value measurement - Hollow concrete block wall greenTEG

Measurement result:

Logger data:

Serial No:	331053		
Type:	U-value measurement kit	Inside temp. (T1):	24.8 °C
Sensitivity:	10.7 uV/(W/m²)	Outside temp. (T2):	26.5 °C
Config.:	CB125BA	Measurement time (t):	506.50 h

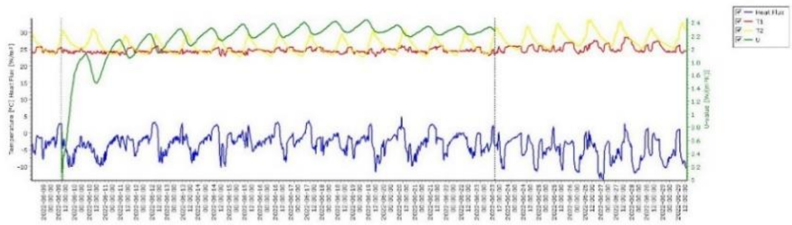
U-value analysis using average method (Section 7.1, ISO 9869-1:2014):

Analysis start time:	2022-06-09 11:37:30	U-value w/o last 24h (U24):	2.29 W/(m²K)
Analysis end time:	2022-06-23 11:37:30	U-value first 2/3 (U2/3):	2.35 W/(m²K)
Analysis period:	336 h	U-value last 2/3 (U2/3):	2.28 W/(m²K)
U-value:	2.27 W/(m²K)	dU24:	-0.9 %
		dU2/3:	2.9 %
		dR24:	1.5 %
		dR2/3:	-4.8 %

Measurement data fulfils requirements of ISO 9869-1:2014 section 7.1.
Uncertainties due to improper installation or environmental influences must be estimated by user (see section 6.1).

Additional comments:

Measurement overview over t=506.50 h



This report has been generated by greenTEG U-value Software v1.02.10 (2022-06-29 15:49:55)

Figure C1.2 U-value measurement - Limestone block wall

Appendix D: Solar Pv system setting up in DesignBuilder

D1.1: Solar PV manufacturer specifications and PV performance model sitting up in DesignBuilder

LG NeON®2

LG400N2W-V5 | LG395N2W-V5

General Data

Cell Properties(Material / Type)	Monocrystalline / N-type
Cell Maker	LG
Cell Configuration	72 Cells (6 x 12)
Number of Busbars	12EA
Module Dimensions (L x W x H)	2,024mm x 1,024mm x 40 mm
Weight	20.3 kg
Glass(Material)	Tempered Glass with AR Coating
Backsheet(Color)	White
Frame(Material)	Anodized Aluminium
Junction Box(Protection Degree)	IP 68
Cables(Length)	1,200 mm x 2EA
Connector(Type / Maker)	MC 4 / MC

Certifications and Warranty

Certifications	IEC 61215-1/-1-1/2:2016, IEC 61730-1/2:2016, UL 1703
	ISO 9001, ISO 14001, ISO 50001
	OHSAS 18001, PV CYCLE
Salt Mist Corrosion Test	IEC 61701 : 2012 Severity 6
Ammonia Corrosion Test	IEC 62716 : 2013
Module Fire Performance	Type 1 (UL 1703)
Fire Rating	Class C (UL 790, ULC/ORD C 1703)
Solar Module Product Warranty	25 Years
Solar Module Output Warranty	Linear Warranty*

* 1) First year : 98% 2) After 1st year : 0.35% annual degradation 3) 89.6% for 25 years

Temperature Characteristics

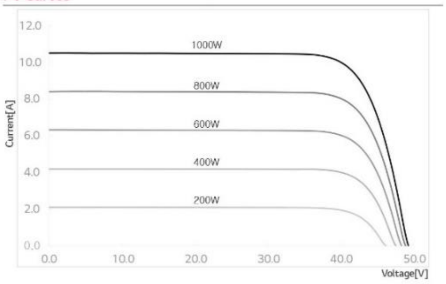
NMOT*	[°C]	42 ± 3
Pmax	[%/°C]	-0.36
Voc	[%/°C]	-0.26
Isc	[%/°C]	0.02

* NMOT (Nominal Module Operating Temperature): Irradiance 800 W/m², Ambient temperature 20 °C, Wind speed 1 m/s, Spectrum AM 1.5

Electrical Properties (NMOT)

Model		LG400N2W-V5	LG395N2W-V5
Maximum Power (Pmax)	[W]	300	296
MPP Voltage (Vmpp)	[V]	38.0	37.7
MPP Current (Impp)	[A]	7.88	7.86
Open Circuit Voltage (Voc)	[V]	46.5	46.4
Short Circuit Current (Isc)	[A]	8.40	8.37

I-V Curves



Electrical Properties (STC*)

Model		LG400N2W-V5	LG395N2W-V5
Maximum Power (Pmax)	[W]	400	395
MPP Voltage (Vmpp)	[V]	40.6	40.2
MPP Current (Impp)	[A]	9.86	9.83
Open Circuit Voltage (Voc, ±5%)	[V]	49.3	49.2
Short Circuit Current (Isc, ±5%)	[A]	10.47	10.43
Module Efficiency	[%]	19.3	19.1
Power Tolerance	[%]	0 ~ +3	

* STC (Standard Test Condition): Irradiance 1000 W/m², Cell temperature 25 °C, AM 1.5

Operating Conditions

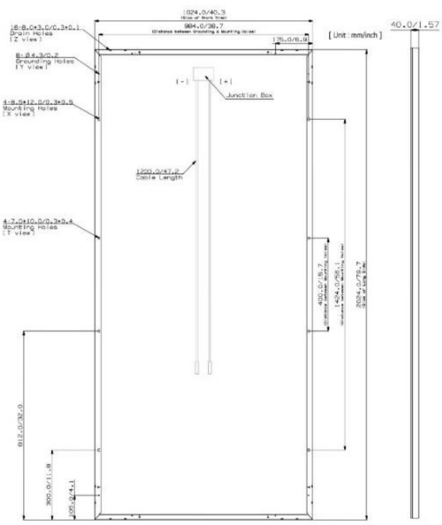
Operating Temperature	[°C]	-40 ~ +90
Maximum System Voltage	[V]	1,500(UL), 1000(IEC)
Maximum Series Fuse Rating	[A]	20
Mechanical Test Load (Front)	[Pa / psf]	5,400 / 113
Mechanical Test Load (Rear)	[Pa / psf]	3,000 / 63

* Test Load = Design load X Safety Factor (1.5)

Packaging Configuration

Number of Modules per Pallet	[EA]	25
Number of Modules per 40ft HQ Container	[EA]	550
Packaging Box Dimensions (L x W x H)	[mm]	2,080 x 1,120 x 1,226
Packaging Box Gross Weight	[kg]	551

Dimensions (mm / inch)



LG Electronics Inc.
Solar Business Division
LG Twin Towers, 128 Yeoui-daero, Yeongdeungpo-gu, Seoul 07336, Korea
www.lg-solar.com

Product specifications are subject to change without notice.
DS-V5-72-W-G-F-EN-90214

Figure D1.1 Solar PV manufacturer specifications

D2: Solar PV settings in DesignBuilder

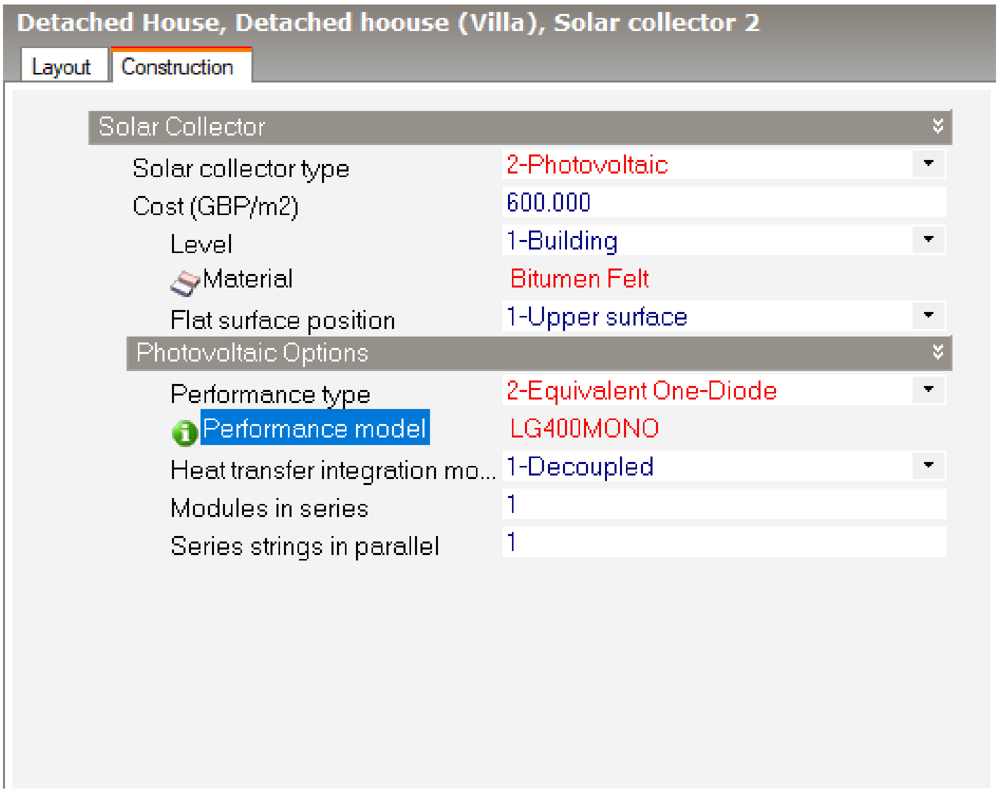


Figure D2.1 Solar collector type selection

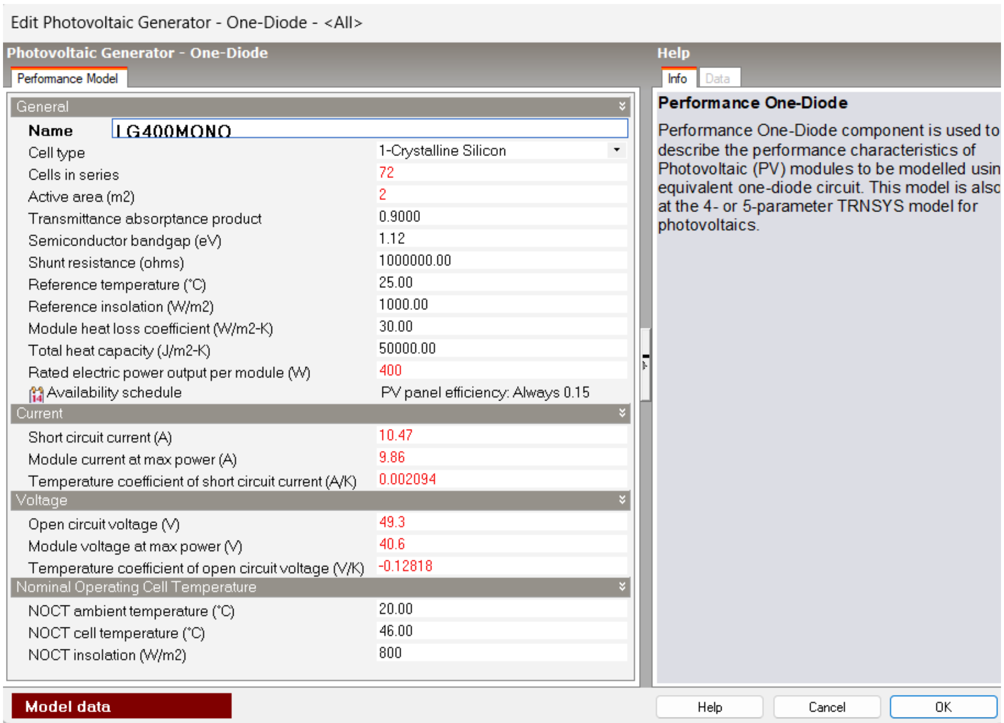


Figure D2.2 Setting up the photovltatic performance model .

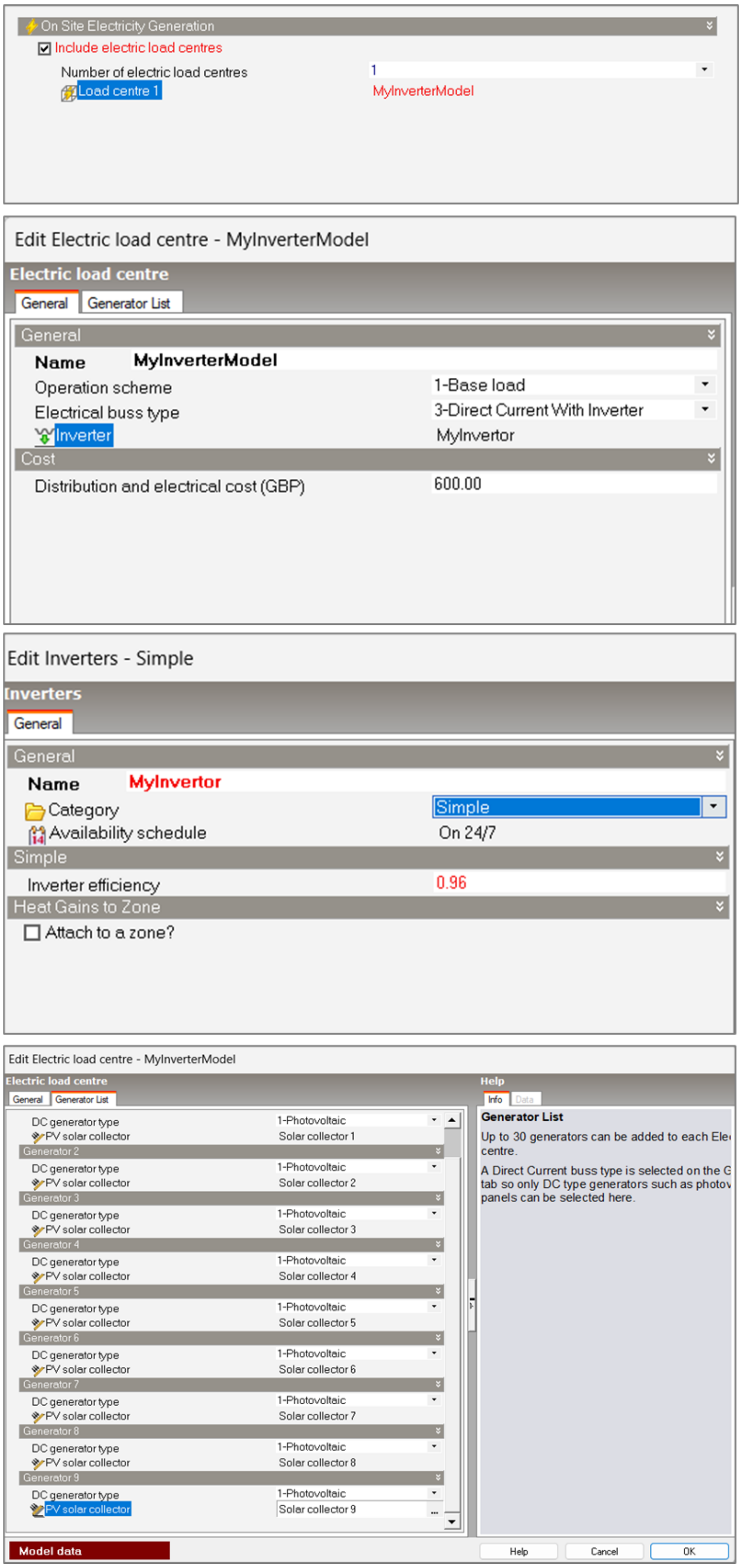


Figure D2.3 Creating inverter model,electrical load centre, and the number of generators