

University of Nottingham
UK | CHINA | MALAYSIA

Passivhaus Standard Applicability for Buildings in Hot and Dry Climate – A Case Study for Saudi Arabia

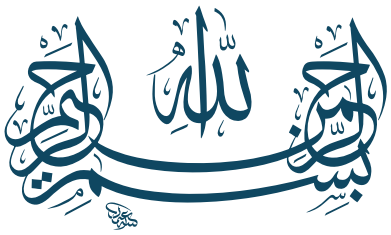
January 2026

Fahad Mohammed Hamad Alrefai

B. Arch. (Hons), M. Arch.

Thesis submitted to the University of Nottingham for the degree of Doctor of Philosophy in Architecture (Science)

QUOTATION



In the name of Allah, the Most Beneficent, the Most Merciful

[قالَ رَبِّ اشرَح لي صَدري ۝ ويَسِّر لي أَمري ۝ واحلُل عُقدَةً مِن لِساني ۝ يَفقَهوا قَولي۝]

القرآن الكريم [سورة طه: ٢٥-٢٨]

Saheeh International (Qur'an 20:25-28):

(25) My Lord, expand [i.e., relax] for me my breast [with assurance]

(26) And ease for me my task

(27) And untie the knot from my tongue

(28) That they may understand my speech

DEDICATION

This thesis is dedicated to my late father, **Mohammed bin Hamad**, my first teacher and mentor, whose encouragement, wisdom, and unwavering support continue to inspire me even after his passing in 2017. His belief in me and constant guidance laid the foundation for every step of my life, particularly my educational journey.

To my great mother, **Haniah Ahmad**, who raised me with love, patience, and strong values, and who has filled my life with joy. Her endless sacrifices, boundless support, and heartfelt prayers have sustained me through the most challenging moments of my studies abroad in the United States and the United Kingdom.

To my brothers, **Turki**, **Meshal**, and **Basel**, and my sisters, **Malak** and **Reham**, for their continuous support, prayers, and encouragement. As the eldest brother, I am honoured that they have looked up to me as a role model, and their pride in my work has motivated me to persevere, even when I missed important family occasions while studying abroad. Their calls and messages during my PhD brought a sense of home and warmth to my life in the UK.

To my beloved wife, **Joury**, whose presence has made this experience in the UK memorable and meaningful. Her patience, understanding, and steadfast support—always standing by my side and sharing the burdens and absences from home—have been a constant source of strength and comfort.

To my precious children, **Kayan** and **Hazem**, God's gifts, whose smiles and innocence brightened the hardest days and reminded me of the true purpose behind my efforts.

Finally, to my late friends, **Turki Alrifaie** and **Muhamad Sendi**, for sharing the ambition for future success and the cherished memories that still live in my heart.

ACKNOWLEDGEMENTS

All praise and unlimited thanks are due to Almighty Allah, whose benevolence and guidance have granted me the strength and patience to complete this research.

I would like to express my sincere gratitude to my supervisor, Dr Siddig Omer, for giving me the opportunity to become a PhD candidate under his supervision and for his invaluable guidance, continuous support, and constructive feedback throughout this PhD. His insightful comments, scientific rigour, and constant encouragement have greatly enriched this research and strengthened its outcomes. I am particularly grateful for his patience, readiness to discuss ideas and challenges, and steady support during difficult stages.

I thank Prof Jo Darkwa for his reviews during the first two years of this PhD. I also thank my friends in the BEE Research Group for their valuable discussions and kindness, which created a productive research environment.

I extend my sincere appreciation to Dr Sara Mohamed and Dr Hassam N. Chaudhry for the time and scholarly expertise they devoted to reviewing this work. The highly constructive recommendations and rigorous intellectual exchange during the *viva voce* examination have significantly strengthened the final thesis.

I am grateful to my Saudi government and my university, Taibah University, for the scholarship that enabled my postgraduate studies, and to my colleagues and friends there whose encouragement and contact provided positive energy to pursue this PhD.

In addition, I am deeply grateful to Mr Ahmad Alerwi Aljuhani, my father's friend, whom I am honoured to call my own friend as well. Thank you for your warm and supportive messages that have meant more to me than words can express.

My warm thanks go to the cherished Al Madinah Professors Team for their generous and unconditional friendship. To my best friend, Dr Wail bin Faris Alsolami, thank you for everything since we became roommates in Jeddah. Your positivity, insightful discussions, and shared laughter have been a true source of strength. Also, to my close friends in Nottingham (Friday Group), your companionship has made this journey easier and more meaningful.

Finally, I thank Prof Fred Andreas, Prof Keith Loftin, and Prof Barbara Ambach for their inspiring architecture studios and valuable lessons during my M.Arch. studies in the USA, and for their kind recommendations that supported my PhD applications.

PUBLICATION AND ACTIVITY

- ALREFAI, F. M. & OMER, S. A. 2023. Classification of climate zone using degree-day method, A Case Study of Saudi Arabia. *In:* RIFFAT, S., ed. 20th International Conference on Sustainable Energy Technologies, 15th – 17 August 2023 Nottingham, UK. University of Nottingham: Buildings, Energy & Environment Research Group, 92-459.
- Single Family Passivhaus Plus Tour by The UK Passivhaus Trust. 30th June 2024, Beeston, Nottingham, UK. A 2-hour visit to see sustainable living in action, a Presentation, a tour with the Project's Architect, and meeting the house's owner.
- Upcoming Conference: SET2026, The 22nd International Conference on Sustainable Energy Technologies. 13-15 August 2026. Kuala Lumpur, Malaysia.

ABSTRACT

The Kingdom of Saudi Arabia targets 70 per cent homeownership by 2030 amid unprecedented residential housing demand. The building sector consumes over 75 per cent of national electricity production, predominantly driven by air-conditioning in the hot and arid climate. Although the Passivhaus standard has demonstrated the potential to reduce building energy use by up to 90 per cent in suitable contexts, its application in Saudi Arabia remains largely unexplored.

This thesis investigates the applicability of core Passivhaus principles and the adaptation of its performance metrics for Saudi residential buildings across five representative climatic zones. Using DesignBuilder for dynamic building energy modelling, validated against empirical data from an existing residence in Madinah, the research develops a refined climatic classification based on meteorological records from 2017–2021, with Madinah, Riyadh, Dammam, Tabuk, and Abha selected as representative cities.

A calibrated baseline energy model, aligned with measured annual electricity consumption, is systematically transferred across the five climates while maintaining consistent geometry, construction, and operational assumptions. Three scenarios, baseline practice, Saudi Building Code (SBC 602) compliance, and the Passivhaus implementation, are evaluated using DesignBuilder simulations. An optimal window-to-wall ratio (WWR) is investigated to support an adapted Passivhaus framework, assessing configurations from 5 to 20 per cent across all climate zones to balance solar gains, daylight provision, and occupant thermal comfort. Passivhaus design principles, including external wall and roof U-values and airtightness, are further optimised to develop climate-specific recommendations.

Results demonstrate annual total site energy reductions of approximately 25–70 per cent through the application of Passivhaus strategies across the five climatic zones, with the greatest savings achieved in Zone Five, Abha, which is the coldest Saudi climate zone. Core Passivhaus design principles remain valid under Saudi conditions; however, the rigid thermal envelope specifications of the European standard require local adaptation to address high cooling loads. Comparative analysis shows that SBC 602 compliance yields more modest energy improvements of around 16–37 per cent relative to conventional construction, with the largest gains occurring in milder climates.

Overall, Passivhaus principles, appropriately adapted to local climatic and regulatory conditions, offer a technically feasible pathway to transformative improvements in residential energy efficiency and thermal comfort in Saudi Arabia, with the optimisation results indicating that climate-sensitive envelope specifications can achieve substantial savings without resorting to extreme insulation levels. The research closes a significant knowledge gap regarding the feasibility, performance, and optimisation of rigorous, performance-based sustainable building standards in hot and arid regions, and provides evidence-based guidance for policymakers, designers, and practitioners engaged in the Kingdom's rapidly expanding housing sector.

Keywords: Passivhaus; Saudi Arabia; Saudi Building Code (SBC); energy efficiency; residential buildings; Building Performance Simulation (BPS); hot and dry climate; climate zoning; window-to-wall ratio; Madinah; Riyadh; Dammam; Tabuk; Abha.

Table of Content

QUOTATION ii

DEDICATION iii

ACKNOWLEDGEMENTS iv

PUBLICATION AND ACTIVITY v

ABSTRACT vi

Table of Content viii

List of Tables xii

List of Figures xvi

1 INTRODUCTION 1

1.1 Study Background 1
1.2 Problem Statement 2
1.3 Importance of Adopting Sustainability 3
1.4 The Aim and Objectives of the Research 5
1.5 Research Questions 6
1.6 Research Methodology 7
1.7 Thesis Structure 11

2 THE SAUDI BUILT ENVIRONMENT 12

2.1 Introduction 12
2.2 Energy in Saudi Arabia 14
2.2.1 Energy Sources and Production 15
2.2.2 Energy Consumption 17
2.3 Sustainability Status of Saudi Building Sector 23
2.3.1 Development of Saudi Sustainable Buildings 24
2.3.2 Saudi Government Rules, Regulations, and Guidelines 26
2.4 Previous Literature Findings 28
2.5 The Research Gap 30

3 CLIMATIC ZONING AND ENERGY INDICATORS 31

3.1 Introduction 31
3.2 Climatic Literature Review 32
3.3 Materials and Methods 37
3.3.1 Climatic Zoning Parameters 37
3.3.2 Degree Days Method 38

3.3.3 Meteorological Data and Degree Days Calculation 39
3.3.4 Cooling Degree Days 42
3.3.5 Heating Degree Days 44
3.4 Results and Discussion 45
3.5 Five Cities Representative Zoning Analysis 48
3.5.1 Overview 48
3.5.2 Climate Zone Number One (Hot-Dry and Humid climates) 51
3.5.3 Climate Zone Number Two (Hot desert or arid climate) 55
3.5.4 Climate Zone Number Three (Hot Humid semi-arid climates) 58
3.5.5 Climate Zone Number Four (Warm and Cold desert climates) 61
3.5.6 Climate Zone Number Five (Cold semi-arid climates) 65
4 PASSIVHAUS STANDARD 69
4.1 Introduction 69
4.1.1 Overview of the standard 69
4.1.2 Passivhaus development 71
4.1.3 Passivhaus main principles 73
4.1.4 Passivhaus certificates 77
4.1.5 Passivhaus classes 78
4.2 Passivhaus Software and Validation 80
4.3 Passivhaus Building Certification Process 81
4.4 Case studies of Passivhaus Projects 82
5 THE BASE CASE STUDY 87
5.1 Introduction 87
5.2 Building Characteristics 87
5.2.1 Location and Profile 87
5.2.2 Construction and Materials 90
5.3 Data Collection 92
5.3.1 Architectural Drawing 94
5.3.2 Actual Energy Consumption 95
5.4 Modelling and Simulation 99
5.4.1 Model Setup in DesignBuilder 100

5.4.2 Baseline Model Validation and Calibration 101
5.4.3 Base Model in other cities 104
5.5 Baseline Model Performance Analysis and Evaluation 105
5.6 Summary of Key Findings 111
6 APPLYING SAUDI BUILDING CODE AND PASSIVHAUS STANDARD 113
6.1 Introduction 113
6.2 Saudi Building Code (SBC) Application 114
6.2.1 Zone One (SBC) 115
6.2.2 Zone Two (SBC) 120
6.2.3 Zone Three (SBC) 121
6.3 Implementing the Passivhaus (PH) 123
6.3.1 Primary Case Study: Madinah (Zone One) 124
6.3.2 Riyadh city (Zone Two) 126
6.3.3 Dammam city (Zone Three) 127
6.3.4 Tabuk city (Zone Four) 128
6.3.5 Abha city (Zone Five) 129
6.4 Summary 131
7 RESULTS AND DISCUSSION 132
7.1 Introduction 132
7.2 Performance Analysis 135
7.3 Interpretation and discussion 138
7.4 Limitations of the Baseline Model 140
7.5 Summary 141
8 ADAPTING PASSIVHAUS FOR SAUDI ARABIA 142
8.1 Introduction 142
8.2 Examining Passivhaus in the Saudi Climate 143
8.3 Optimising Performance for the Saudi Climate 145
8.3.1 Optimising Building Energy Performance by WWR 145
8.3.2 Normalisation and Performance Evaluation 156
8.4 Optimising Passivhaus Parameters 166
8.4.1 Optimising External Wall U-value 166
8.4.2 Optimising Roof U-value 173
8.4.3 Combined Envelope Optimisation 173

8.4.4 Airtightness Sensitivity Analysis 178

8.5 The Adapted Passivhaus Framework 187
8.6 Summary 188

9 CONCLUSIONS 189

9.1 Research Findings 189
9.2 Recommendations 191
9.3 Contribution to knowledge 192
9.4 Challenges and limitations 193
9.5 Future work 193

REFERENCES 194

APPENDIX 202

List of Tables

Table 2.1. KSA peak load and Available Capacities in 2020 15

Table 2.2. Peak load time and consumption in KSA 15

Table 2.3. Saudi Customers and Energy Sales (GWh) in 2020 source (WERA, 2020) 19

Table 2.4. Saudi Building Code summary 27

Table 3.1 Regions of Saudi Arabia 31

Table 3.2. Selected Saudi Weather Stations 40

Table 3.3. Five Years Average (2017 to 2021) Cooling Degree Days with varying base temperatures* 42

Table 3.4. Five-Year Average (2017–2021) Heating Degree Days with varying base temperatures* 44

Table 3.5 demonstrates the recommended climatic zones of Saudi Arabia, which classification has five zones. At 20 °C, the maximum CDD value of 4044 was recorded in Jizan, while the lowest 814 was recorded in Abha.

Table 3.5. Categorising of Average CDD Values from 2017 to 2021 46

Table 4.1. Passivhaus certification aspects for Central European climates 79

Table 4.2. Locations climatic characteristics 82

Table 4.3. Envelope U-value thermal transmittance of MBRSC (Energy Plus Project 2016) 83

Table 4.4. Dubai Passivhaus Building Information 84

Table 4.5. Primary features of the Italian Passivhaus project 85

Table 5.1 Base Case Study: Location and Profile 89

Table 5.2 Baseline Building Geometry & Characteristics 91

Table 5.3 Typical Occupancy Profiles Across Investigated Cities 92

Table 5.4 Base Case Study Elevation Profile 94

Table 5.5. Monthly and Annual Electricity Consumption for Madinah Case 95

Table 5.6. Actual and Estimated Monthly Electricity Consumption 102

Table 5.7. Case Study Site and Source Energy 106

Table 5.8. Simulated Energy Performance of the Madinah Case Study 107

Table 5.9. Riyadh Base Model Performance in 2023..... 107

Table 5.10. Dammam Base Model Performance in 2023 108

Table 5.11. Tabuk Base Model Performance in 2023..... 109

Table 5.12. Abha Base Model Performance in 2023 110

Table 6.1 Saudi Building Code Maximum Requirements (SBC 602-2018)..... 114

Table 6.2 SBC Model HVAC Input Values 114

Table 6.3. SBC Model's Site and Source Energy in Madinah..... 115

Table 6.4. Madinah's SBC Modelling Subcategory Usage..... 116

Table 6.5. SBC Model (Riyadh)..... 117

Table 6.6. SBC Model (Dammam) 118

Table 6.7. Simulated Energy Performance: Baseline vs. SBC Models in Madinah 119

Table 6.8. Simulated Energy Performance: Baseline vs. SBC Models in Riyadh 119

Table 6.9. Simulated Energy Performance: Baseline vs. SBC Models in Dammam 119

Table 6.10. SBC Model for Tabuk City 120

Table 6.11. Simulated Energy Performance: Baseline vs. SBC Models in Tabuk120

Table 6.12. Abha SBC Scenario Simulation..... 121

Table 6.13. Simulated Energy Performance: Baseline vs. SBC Models in Abha 122

Table 6.14 Passivhaus Model Input Specification 123

Table 6.15. Comparison of Madinah's PH and Baseline Model..... 124

Table 6.16. Madinah PH Energy Performance 125

Table 6.17. Simulated Energy Performance: Riyadh Baseline and Passivhaus Model 126

Table 6.18. Dammam Case Study 127

Table 6.19. Zone Four Represented City 128

Table 6.20. Simulated Models for Abha City..... 129

Table 6.21 Comparison of Total Site Energy Savings between the SBC and Passivhaus Standards Across Five Saudi Cities 131

Table 8.1. Passivhaus Feasibility in Saudi Climates 143

Table 8.2 Madinah PH Model Performance with Various WWR..... 146

Table 8.3 Riyadh Passivhaus Model Performance with Various WWR 149

Table 8.4 Dammam Passivhaus Model Performance with Various WWR 151

Table 8.5 Tabuk Passivhaus Model Performance with Various WWR 153

Table 8.6 Abha Passivhaus Model Performance with Various WWR 155

Table 8.7 Normalised Values for the Energy and Comfort in Madinah 158

Table 8.8 Average Normalised Value in Zone One 158

Table 8.9 Average Normalised Value in Zone Two 160

Table 8.10 Average Normalised Value in Zone Three..... 162

Table 8.11 Average Normalised Value in Zone Four 163

Table 8.12 Average Normalised Value in Zone Five..... 164

Table 8.13 PH External Wall Optimisation and Comparison for the Five Selected Saudi Cities 167

Table 8.14 Impact of Wall U-Value on Passivhaus Model Scenarios in Madinah168

Table 8.15 Impact of Wall U-Value on Passivhaus Model Scenarios in Riyadh . 169

Table 8.16 Impact of Wall U-Value on Passivhaus Model Scenarios in Dammam 170

Table 8.17 Impact of Wall U-Value on Passivhaus Model Scenarios in Tabuk .. 171

Table 8.18 Impact of Wall U-Value on Passivhaus Model Scenarios in Abha 172

Table 8.19 Comparative Annual Energy Consumption in Madinah 174

Table 8.20 Comparative Annual Energy Consumption in Riyadh 175

Table 8.21 Comparative Annual Energy Consumption in Dammam..... 175

Table 8.22 Comparative Annual Energy Consumption in Tabuk 176

Table 8.23 Comparative Annual Energy Consumption in Abha..... 177

Table 8.24 Airtightness Sensitivity Results for Madinah 179

Table 8.25 Airtightness Sensitivity Results for Riyadh 181

Table 8.26 Airtightness Sensitivity Results for Dammam..... 183

Table 8.27 Airtightness Sensitivity Results for Tabuk 184

Table 8.28 Airtightness Sensitivity Results for Abha..... 186

Table 8.29 Comparison of Building Performance Parameters..... 188

Table 0.1. Climatic Data of Selected Saudi Cities source: SBC 602 205

Table 0.2. Weather stations in Saudi Arabia source: (Said, Habib et al. 2003) 206

Table 0.3. ASHRAE climate zoning for Saudi Arabia (ASHRAE, 2021) 207

Table 0.4. Simulated Energy Performance: Baseline vs. SBC Models in Madinah 208

Table 0.5. Simulated Energy Performance: Baseline vs. SBC Models in Riyadh 208

Table 0.6. Simulated Energy Performance: Baseline vs. SBC Models in Dammam 208

Table 0.7. Simulated Energy Performance: Baseline vs. SBC Models in Tabuk 208

Table 0.8. Simulated Energy Performance: Baseline vs. SBC Models in Abha .. 208

List of Figures

Figure 1.1. Sustainability triangle (Cainthus 2020) 3

Figure 1.2. Home ownership in Saudi Arabia (GAStat 2020) 4

Figure 1.3 Workflow of the Research Methodology 8

Figure 2.1. Map of The Kingdom of Saudi Arabia (free world maps 2021)..... 12

Figure 2.2.Saudi Arabia's electric power generating in 2020 14

Figure 2.3. Petroleum and other liquids produced and consumed in SA (U.S. EIA 2021) 16

Figure 2.4. Dry natural gas production of KSA (U.S. EIA 2021) 16

Figure 2.5. Saudi residential electricity usage per capita from 2015 to 2020 17

Figure 2.6. SEC Customer number for different sectors (ECRA 2019) 18

Figure 2.7. KSA and global per capita energy consumption from 2000 to 2020. 19

Figure 2.8. Energy Used (TWh) in KSA from 2000 to 2015 (SEC 2021) 21

Figure 2.9. Saudi Arabia Energy Usage in 2020 source (WERA 2020)..... 21

Figure 3.1. Elevation of Saudi Arabia and Weather Stations Map (Amin, Mahmoud et al. 2016)..... 32

Figure 3.2. The Köppen-Geiger climate classification map from 1980 to 2016 (Beck, Zimmermann et al. 2018) 33

Figure 3.3. Monthly Temperatures of SA from 1991 to 2020 (World Bank 2021)34

Figure 3.4. Building Code climatic Zones in SA source: (SBC 602 2018) ... 35

Figure 3.5 Saudi Arabia's Climatic Zones (Alrashed and Asif 2014)..... 36

Figure 3.6. Saudi Arabia Contouring Map of CDD (Al-Hadhrami 2013) ... 36

Figure 3.7 Metrological Stations in Saudi Arabia..... 39

Figure 3.8. CDD for Saudi Cities with a base temperature of 20 °C 43

Figure 3.9. Saudi Regions Average CDD Values for Five Years at 20 °C (2017-2021) 45

Figure 3.10. Saudi Arabia Recommended Climatic Zoning base map: vemaps.com..... 47

Figure 3.11. Cities Representing the Saudi Climate Zone 48

Figure 3.12. Annual CDD of the Selected Cities for 2020,2021 and 2022..... 49

Figure 3.13. CDD for Five Saudi Cities with Various Base Temperatures..... 50

Figure 3.14. Average Wind Speed for Five Saudi Cities © WeatherSpark.com 51

Figure 3.15 Monthly CDD of Madinah for 2020, 2021, and 2022..... 51

Figure 3.16. Comfort Zone Chart for Medina © WeatherSpark.com.... 52

Figure 3.17. Average Seasonal Temperatures in Medina © WeatherSpark.com 52

Figure 3.18. Average Relative Humidity in Madinah data source: climate-data.org 53

Figure 3.19. Historical Weather Data for Medina (meteoblue 2023)... 54

Figure 3.20. Average Monthly Wind Speed in Medina © WeatherSpark.com 54

Figure 3.21. Average Hourly Temperature in Riyadh © WeatherSpark.com 55

Figure 3.22. Average Seasonal Temperatures in Riyadh © WeatherSpark.com55

Figure 3.23. Average Relative Humidity in Riyadh data source: climate-data.org 56

Figure 3.24. Historical Weather Data for Riyadh (meteoblue, 2023) 56

Figure 3.25. Average Monthly Wind Speed in Riyadh © WeatherSpark.com . 57

Figure 3.26. Average Hourly Temperature in Dammam © WeatherSpark.com 58

Figure 3.27. Average Seasonal Temperatures in Dammam ©WeatherSpark.com 59

Figure 3.28. Average Relative Humidity in Dammam data source: climate-data.org 59

Figure 3.29. Historical Weather Data for Dammam (meteoblue, 2023) 60

Figure 3.30. Average Monthly Wind Speed in Dammam © WeatherSpark.com 61

Figure 3.31 Average Hourly Temperature in Tabuk © WeatherSpark.com 61

Figure 3.32. Average Seasonal Temperatures in Tabuk ©WeatherSpark.com 62

Figure 3.33. Average Relative Humidity in Tabuk data source: climate-data.org 63

Figure 3.34. Historical Weather Data for Tabuk (meteoblue, 2023) 64

Figure 3.35. Average Monthly Wind Speed in Tabuk © WeatherSpark.com .. 64

Figure 3.36. Average Hourly Temperature in Abha © WeatherSpark.com 65

Figure 3.37. Average Seasonal Temperatures in Abha ©WeatherSpark.com . 66

Figure 3.38. Humidity for Abha data source: climate-data.org .. 66

Figure 3.39. Historical Weather Data for Abha (meteoblue, 2023) 67

Figure 3.40. Average Monthly Wind Speed in Abha © WeatherSpark.com 68

Figure 4.1. Fundamental principles of a Passive House (Feist 2006)..... 70

Figure 4.2. The First Passivhaus project (PHP 2021)..... 72

Figure 4.3. Passivhaus standard requirements (PHI 2015)..... 73

Figure 4.4. Summarising the Passivhaus Main Principles (PEDRANTI 2016) 76

Figure 4.5. Passivhaus criteria (PHI 2022) 77

Figure 4.6. Passivhaus certification classes (PHI 2021)..... 78

Figure 4.7. Building certification process (Passivhaus Trust 2021)..... 81

Figure 4.8. The Passivhaus building in Dubai, UAE (Verfasser der 2016)..... 83

Figure 4.9. Baytna project, Barwa City in Qatar (Fahy 2013)..... 86

Figure 5.1. Site located in Madinah source: The Earth Observatory, NASA . 87

Figure 5.2. Case Study Neighbourhood in Madinah source: SPL ©2024 88

Figure 5.3. Typical Clay block construction in SA Source: (Felimban 2024)... 90

Figure 5.4. Saudi Typical Concrete Building Construction (Alayed, O'hegarty et al. 2021) 90

Figure 5.5. The Case Study Architectural Plan Drawing source: Architecture Office 94

Figure 5.6. Collected Monthly Bills from SEC of the Case Study 96

Figure 5.7. Base Case Study Energy Consumption in 2023 98

Figure 5.8. Madinah's Baseline Performance Study in 2023 98

Figure 5.9 The Baseline Model in DesignBuilder 100

Figure 5.10. Base Model Electricity Bills and DesignBuilder Simulation Result.. 103

Figure 5.11. Comparing Utility and Simulated Monthly Electricity Use in 2023. 104

Figure 5.12. A 3-D Isometric of the Residential Building in Madinah 105

Figure 5.13 . 2-D Illustration of the Building Geometry 106

Figure 5.14 Baseline Model Simulated in Five Saudi Cities 111

Figure 6.1. PH Performance in Riyadh 127

Figure 6.2 PH Performance in Dammam 128

Figure 6.3 PH Performance in Tabuk 129

Figure 6.4. PH Energy Performance in Abha 130

Figure 7.1. Comparing Baseline Model, SBC, and PH in Madinah 133

Figure 7.2. Different Standards Comparison Across Saudi Arabia 135

Figure 7.3. Total Site Energy Saving for SBC vs. Baseline Across Five Saudi Cities 136

Figure 7.4. Total Site Energy Saving for PH vs. Baseline Across Five Saudi Cities 137

Figure 7.5 Total Site Energy Saving for PH on SBC Models Across Five Saudi Cities 138

Figure 7.6. Comparing SBC and PH on the Baseline Models 139

Figure 8.1 Zone One Optimised Scenario with Various WWR 159

Figure 8.2 Zone Two Optimised Scenario with Various WWR 161

Figure 8.3 Zone Three Optimised Scenario with Various WWR 162

Figure 8.4 Zone Four Optimised Scenario with Various WWR 164

Figure 8.5 Zone Five Optimised Scenario with Various WWR 165

Figure 8.6 Energy Consumption Analysis for Zone Five 178

Figure 8.7 Airtightness Impact on Annual Energy Consumption in Madinah 180

Figure 8.8 Airtightness Impact on Annual Energy Consumption in Riyadh 181

Figure 8.9 Airtightness Impact on Annual Energy Consumption in Dammam .. 183

Figure 8.10 Airtightness Impact on Annual Energy Consumption in Tabuk..... 185

Figure 8.11 Airtightness Impact on Annual Energy Consumption in Abha..... 186

Figure 0.1. Passivhaus principles source:(PHI 2016)..... 202

Figure 0.2. Alternative PH standard source:(PHI 2023) 202

Figure 0.3. Creating SBC Requirements Template..... 204

Figure 0.4. Double-glazed window utilised in Madinah SBC 204

Figure 0.5. Zone 1 Wall requirements as SBC 205

Fig 0.6. My participation in the Engineering Showcase event 2022..... 209

Figure 0.7. HVAC system designed (Passive House Institute 2019) 211

Figure 0.8. Recommended ERV System 211

Figure 0.9 SASO Energy Efficiency Label for Selected LG Split AC Unit..... 212

Figure 0.10 PHPP calculations for Dubai Project (MBRSC)..... 213

1 INTRODUCTION

1.1 Study Background

In most nations, the building sector accounts for a significant share of final energy use (Wang, Kuckelkorn et al. 2017). Buildings are also a major source of carbon emissions, responsible for around 35 per cent of global energy consumption (Passivhaus Trust 2021). Thus, buildings are one of the primary sources of global energy consumption and greenhouse gas emissions. In the United Kingdom, for instance, homes consume 28 per cent of total energy, accounting for 22 per cent of total end-user emissions (Mitchell and Natarajan 2020). At the same time, global per capita energy consumption has increased, particularly in developed countries.

In comparison, the Saudi buildings sector consumed 47.6 per cent of all electricity produced in 2020, with a growth rate of about 5 per cent annually (WERA 2020, SEEC 2021).
In the same year, electricity consumption in Saudi Arabia reached 8,263 kWh per capita (WERA 2020). This high energy consumption makes the Kingdom one of the developing countries with the highest energy consumption per capita worldwide. In addition, Saudi Arabia's per capita energy consumption was more than four times higher than the world's average per capita consumption (Ritchie, Roser et al. 2020). Reducing energy demand in the built environment therefore has significant potential to cut greenhouse gas emissions and diminish the environmental impacts associated with power generation (Al-Sanea, Zedan et al. 2016).

In Saudi Arabia, growth in per capita electricity consumption, rising per capita carbon emissions and rapid expansion of the building stock are closely linked to economic and population growth (Al-Tamimi 2017). These trends underscore the urgency of improving the energy performance of buildings and adopting more sustainable construction practices.

1.2 Problem Statement

Among the Gulf Cooperation Council (GCC) countries, the Kingdom of Saudi Arabia (KSA) has the largest and fastest-growing building industry (Mujeebu and Alshamrani 2016). In Saudi Arabia, several factors create an urgent need to embed sustainability within this sector, including limited natural resources, economic and environmental impacts, rapid urbanisation, and growing social awareness (Al Surf, Susilawati et al. 2013). Moreover, residential buildings in Saudi Arabia account for the largest proportion of the energy consumption in the buildings sector, which approaches 46% (ECRA 2019). This high energy usage makes the Saudi residential industry unsustainable. A major contributing factor is that most residential buildings, including detached houses (villas) and blocks of flats (apartments' building), lack key sustainable features, such as effective thermal insulation.

According to the Saudi Housing Program, Saudi families are expected to own 70% of their homes by 2030 under the newly released Saudi Vision 2030 (Saudi Vision 2030 2021). Indeed, the Saudi residential market is expected to witness significant growth over the next few years to meet the Saudi Vision 2030 goals in the residential aspect and fulfil the demand for new housing units. In 2018, the Ministry of Housing and the REDF, for instance, launched the Sakani programme to assist Saudi citizens in purchasing their first home (JLL 2022). Without a robust sustainability framework, this projected growth risks locking in high energy demand and associated emissions for decades.

There is therefore a strong case for adopting an established sustainable building framework, such as the Passivhaus standard, which has gained international recognition for its performance. Passivhaus buildings can reduce heating and cooling energy demand by up to 90 per cent compared with conventional buildings, and by more than 75 per cent compared with typical new construction, while also providing high levels of indoor comfort (PHI 2021). Examining the applicability of the Passivhaus standard to Saudi residential buildings offers a promising pathway to address the identified challenges.

1.3 Importance of Adopting Sustainability

Public awareness is widely recognised as a critical factor in the successful implementation and further development of sustainability measures in Saudi construction projects (Al Surf, Balabel et al. 2021). Sustainability is becoming increasingly contentious, as Figure 1.1 indicates the three fundamental sustainability elements, including environmental, social, and economic factors, which the UN defined in 2005 (Cainthus 2020).

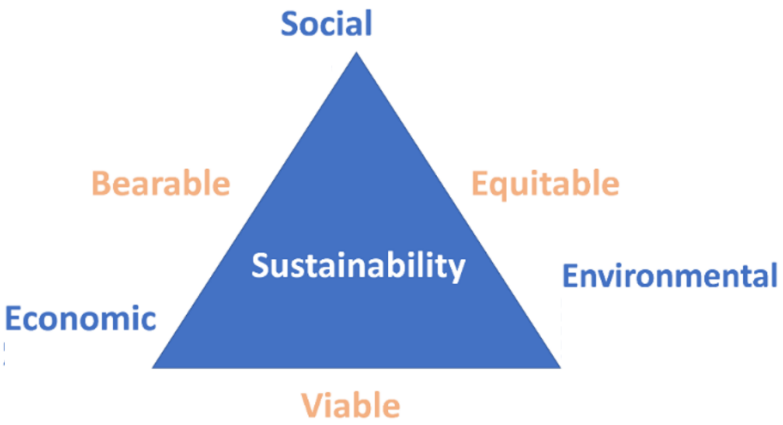


Figure 1.1. Sustainability triangle (Cainthus 2020)

(Al Surf, Susilawati et al. 2014) argues that 'developing sustainable housing in Saudi Arabia is a must for the preservation of resources for future generations of the region and the world.' A sustainable built environment is frequently defined as development that fulfils contemporary requirements while preserving the capacity of future generations to satisfy their own (Al Surf, Balabel et al. 2021). Worldwide, the importance of sustainable construction to conserving natural resources is widely acknowledged. Natural resource availability in every country can lead to economic development and a higher quality of life for its citizens (Al Surf, Susilawati et al. 2014). The world's most important non-renewable natural resources include natural gas, oil, and coal. However, without sustainable management for future generations, these natural resources will be depleted in the coming years.

Nevertheless, Saudi Arabia continues to rely heavily on oil and natural gas for energy production, making the conservation of these resources particularly important. Thus, the adoption of sustainable building standards can contribute to preserving primary resources while improving environmental performance. In other words, incorporating sustainable applications into the built environment of the Kingdom has many advantages for future generations, such as saving the country's natural resources.

Indeed, a country like Saudi Arabia is in a favourable position to embed sustainability concepts while large numbers of projects are still under development (Al Surf, Susilawati et al. 2014).

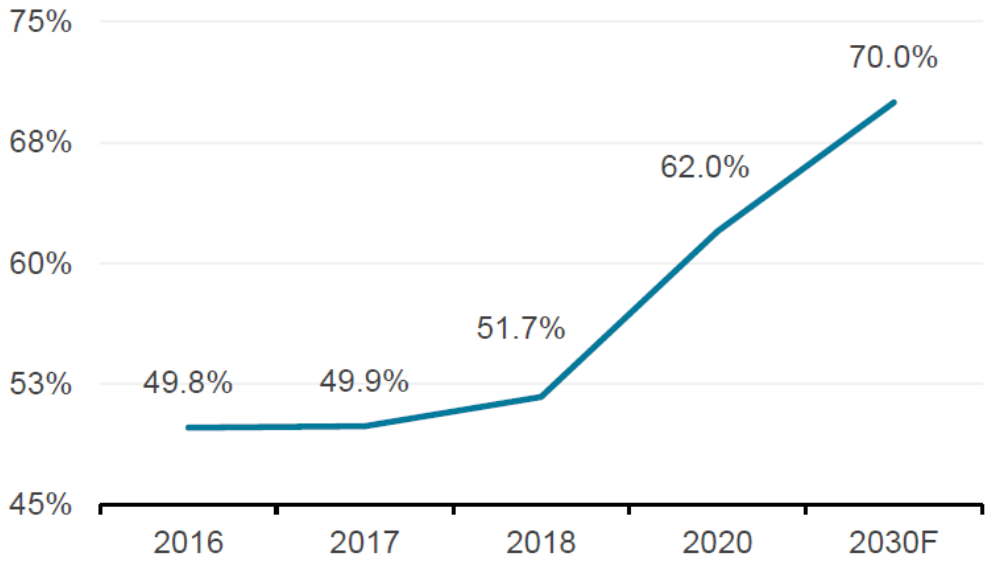


Figure 1.2. Home ownership in Saudi Arabia (GAStat 2020)

Meanwhile, Figure 1.2 illustrates a noticeably sharp increase in construction projects between 2018 and 2020. Also, the growth continues as projected to reach the summit in 2030, to 70 per cent. This construction development highlighted the importance of implementing a sustainable framework.

1.4 The Aim and Objectives of the Research

This research study examines applying the Passivhaus standard to the residential building sector in Saudi Arabia and evaluates its potential impacts. It focuses on evaluating and improving the efficiency of housing units, including energy performance and thermal comfort. The research focuses on the Passivhaus standard for the hot and dry climate countries, a case study of the Kingdom of Saudi Arabia. The aim is to develop a framework for upgrading existing and new residential flats and houses to the Passivhaus standard.

The research study has several key objectives to achieve its goal as follows:

1. Analyse the climatic conditions of Saudi Arabia, including trends and fluctuations relevant to residential building performance.
2. Assess the energy performance of conventionally constructed residential buildings in Saudi Arabia to identify performance gaps relative to Passivhaus.
3. Identify key Passivhaus design and performance characteristics, with particular emphasis on strategies for reducing cooling energy demand in hot and dry climate countries.
4. Examine the Saudi Building Code (SBC), focusing on the Saudi Energy Conservation Code (SBC 602-2018).
5. Evaluate, through building energy simulations, the thermal and energy performance of buildings designed or retrofitted in line with the Passivhaus.

1.5 Research Questions

Well-designed buildings can maintain relatively stable indoor temperatures through appropriate passive design and sustainable construction techniques, thereby reducing reliance on mechanical cooling and other energy-intensive systems. This study therefore addresses the following research questions, which form the foundation for this study's aims:

- What are the key international requirements and performance criteria of the Passivhaus standard for residential buildings?
- What is the current energy performance of residential buildings in Saudi Arabia, particularly in terms of annual electricity consumption?
- To what extent have Passivhaus principles been adopted in the Saudi residential construction sector?
- What are the expected impacts of adopting the Passivhaus standard in Saudi residential buildings?
- Are the existing Passivhaus standard for hot climates applicable in Saudi Arabia, or do they require adaptation to local climatic and regulatory conditions?

1.6 Research Methodology

Qualitative research involves collecting, analysing and interpreting data that cannot easily be reduced to numbers (Anderson 2010). Quantitative research consists of collecting data that can be quantified and statistically processed to support or disprove alternative knowledge claims (Williams 2011). Although, 'Qualitative and quantitative approaches should not be viewed as rigid, distinct categories, polar opposites, or dichotomies; instead, they represent different ends on a continuum' (Creswell 2014). Employing a mixed-methods strategy is therefore appropriate for this study, as it enables the strengths of both approaches to be combined to provide a richer understanding of the applicability of Passivhaus to Saudi residential buildings.

This research adopts a quantitative, simulation-based methodology grounded in empirical data from a representative residential building case study, as summarised in Figure 1.3. The approach combines detailed data collection from an existing flat, development and validation of the building energy model in DesignBuilder, sequential application of the Saudi Building Code (SBC) and Passivhaus criteria (PH), based on the refined climatic zoning for Saudi Arabia established in a conference paper published during this PhD study.

The empirical basis of the study is a single base-case residential flat located in Madinah, Saudi Arabia, constructed using typical local practices with no thermal insulation in the building envelope. Official architectural drawings for this flat are collected, together with monthly electricity bills for a complete year (2023), providing measured whole-building electricity consumption data for model calibration. These data are used to characterise the base case in terms of geometry, construction assemblies, occupancy patterns, installed systems and actual energy use.

A dynamic building energy model of the case-study flat is then developed in DesignBuilder, representing whole-building electricity consumption over the year. The model is calibrated against the measured monthly bills so that the simulated results closely reproduce the observed energy-use profile, and the validated model serves as a baseline for assessing the impact of successive design and regulatory interventions. The calibrated base-case model is subsequently adapted to the remaining representative Saudi climatic zones by applying the appropriate weather files for their corresponding cities, while maintaining the same building geometry, construction and usage characteristics.

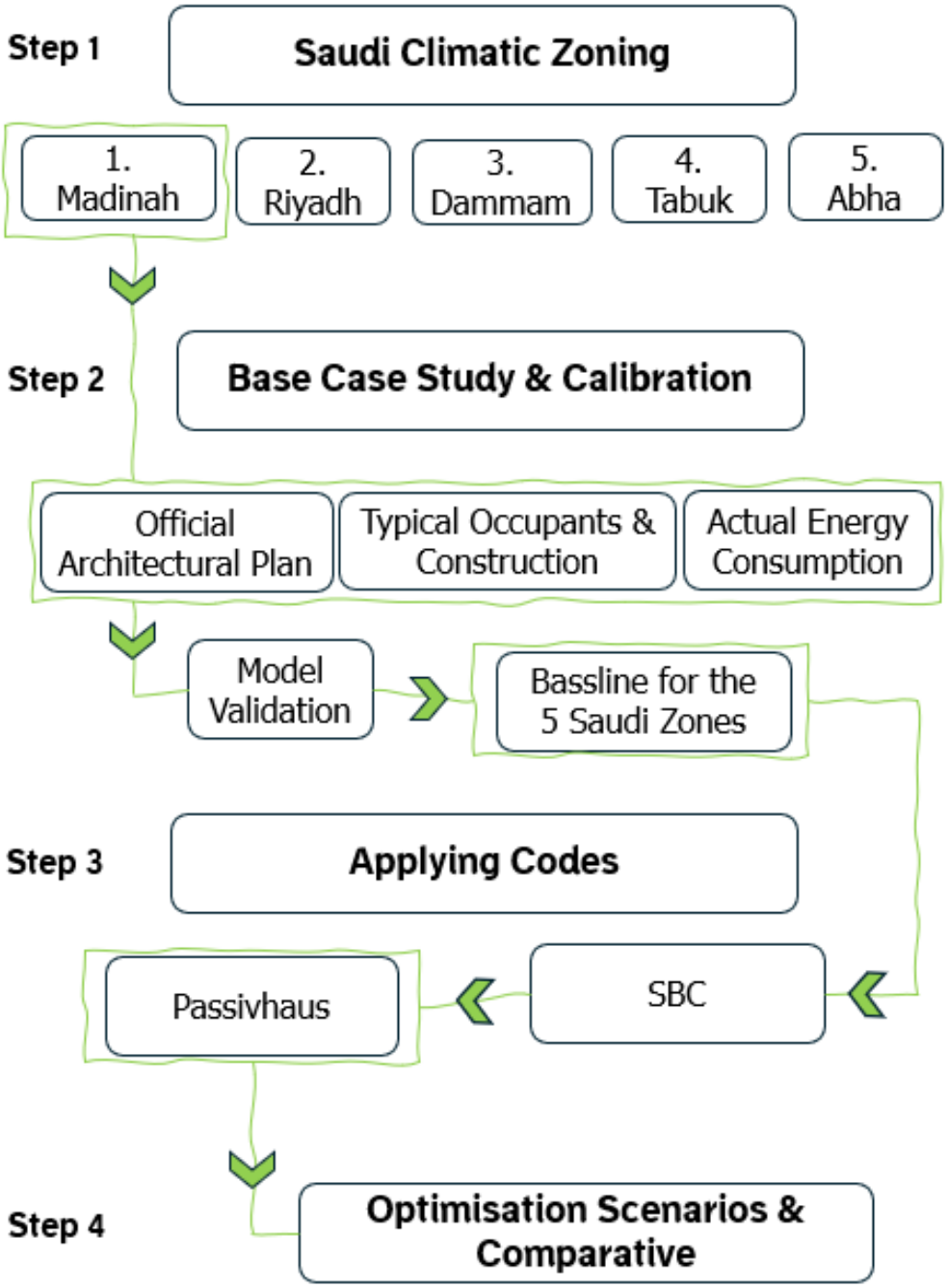


Figure 1.3 Workflow of the Research Methodology

Figure 1.3 depicts the research methodology as four individual steps, each comprising specific tasks as described below.

1. Saudi Climatic Zoning

This step defines five representative Saudi climatic zones, represented by Madinah (Zone 1), Riyadh (Zone 2), Dammam (Zone 3), Tabuk (Zone 4) and Abha (Zone 5), based on a conference paper published during the PhD study.

2. Base case model development and calibration

Second step includes the collection of case-study data for the base-case flat in Madinah, such as architectural plan, 2023 monthly electricity bills, local weather files and the relevant requirements of the Saudi Building Code and Passivhaus standard. It also includes a dynamic energy model of the Madinah flat is developed in DesignBuilder and calibrated against the measured whole-building monthly electricity consumption. The calibrated model is then transferred to the remaining four cities by applying their respective climatic data, while keeping building geometry, construction and usage characteristics constant, thereby establishing base-case models for all five climatic zones.

3. Codes Implementing and Scenarios Development

Step three generates three principal scenarios for every climate zone: an Existing scenario representing the calibrated base-case dwelling; an SBC-compliant scenario that meets the Saudi Building Code and Saudi Energy Conservation Code requirements; and a Passivhaus (PH) scenario in which full Passivhaus design principles, adapted to local climatic conditions, are implemented.

4. Optimisation and Comparative Analysis

In the final step, the Passivhaus scenarios are further optimised in each climate zone by systematically varying wall and roof U-values and the level of airtightness within realistic ranges. Energy consumption and specific thermalperformance metrics, namely operative temperatures, unmet cooling hours, and discomfort hours (ASHRAE 55), are then compared across an existing base case, the SBC, the Passivhaus standard, and optimised Passivhaus scenarios for all five cities, providing an integrated assessment of the feasibility and benefits of adopting the Passivhaus standard in the Saudi residential sector.

Within this overall framework, the research methods comprise several interrelated components. First, a comprehensive literature review of academic and professional sources on Passivhaus, sustainable housing, Saudi climatic zoning and energy indicators, and the Saudi residential sector is conducted to establish the conceptual and empirical foundations of the study. Second, the refined climatic zoning of Saudi Arabia and associated energy indicators are used to define the five representative climatic zones and their cities, which form the context for the numerical analysis. Third, detailed architectural, operational and energy-consumption data for the base-case flat and for each climatic zone are collected and used to develop and calibrate the DesignBuilder model and to adapt it to the five zones. Fourth, SBC-compliant and full Passivhaus scenarios are generated for each zone, and finally a comparative analysis of all scenarios is performed, focusing on key energy and thermal-comfort indicators while optimising selected Passivhaus parameters—specifically wall and roof U-values and airtightness levels—to derive context-appropriate design recommendations for Saudi residential buildings.

Indeed, this structured methodology enables a systematic comparison between current practice, national regulatory standards and Passivhaus-based design solutions across the principal Saudi climatic zones, thereby assessing the feasibility and potential benefits of adopting the Passivhaus standard in the Saudi residential sector.

1.7 Thesis Structure

The PhD thesis is organised into nine chapters as follow:

Chapter 1 introduces the research by outlining the background, problem statement, aim and objectives, research questions, methodology and overall structure of the study.

Chapter 2 examines the Saudi built environment, presenting key statistics on energy sources, production and consumption, and discussing the implications of rapid urbanisation for the residential sector.

Chapter 3 describes the Saudi climatic zoning system and sets out the main energy indicators relevant to building performance.

Chapter 4 reviews the Passivhaus standard and summarises selected international case studies, before considering the status of Passivhaus-related developments in Saudi Arabia.

Chapter 5 introduces the base-case residential study and details its physical, operational and energy-use characteristics.

Chapter 6 explains the application of the Saudi Building Code and the Passivhaus standard to the base-case study, including the development of retrofit and design scenarios.

Chapter 7 presents and discusses the results of the simulation analyses, focusing on energy performance, thermal comfort and other relevant indicators.

Chapter 8 explores the adaptation of the Passivhaus standard for Saudi Arabia, drawing on the findings to propose a context-specific framework for residential buildings.

Chapter 9 summarises the main conclusions, highlights the contributions of the research, outlines its limitations and proposes directions for future work.

2 THE SAUDI BUILT ENVIRONMENT

2.1 Introduction

The Kingdom of Saudi Arabia (KSA), as shown in Figure 2.1, is located in the Arabian Peninsula. The country's land elevation varies between 0 and 3000 meters above mean sea level, which is 2.3 million square kilometres (Alrashed and Asif 2015). The Kingdom lies between latitudes 16° 22′ 46″ and 32° 14′ 00″ N, and longitudes 34° 29′ 30″ and 55° 40′ 00″ E (Saudi Ministry of Media 2020). According to the Saudi General Authority for Statistics, Saudi Arabia's population exceeded 35 million by mid-2020. KSA is one of the fastest-growing developing countries in the world. Saudi Arabia's population annual growth rate was 2.40 per cent in 2019, according to the General Authority for Statistics (GAStat) of Saudi Arabia (GAStat 2020). Moreover, in 2018, there were 5,466,910 housing units in the Kingdom (Al-Tamimi 2021).



Figure 2.1. Map of The Kingdom of Saudi Arabia (free world maps 2021)

Significant cities in Saudi Arabia after the capital city Riyadh are Makkah Al Mukarramah (Mecca), Al Madinah Al Munawarah (Medina), Jeddah, Dammam, Al Taif (Ta'if), and Tabuk. These cities are essential for several reasons, such as having most of the country's new construction projects, the majority of the population, the largest Saudi cities, and is located in various climate zones. Saudi Arabia features a distinct historical landscape that has evolved over the years, including six UNESCO World Heritage Sites, including a unique cultural landscape named Al-Ahsa Oasis. In addition, the Kingdom has the world's second-largest proven oil reserves (EIC 2019). Saudi Arabia's climate is primarily described as hot and dry because of the high radiation intensity.

Saudi Arabia maintains three significant oil facts such as (1) owning 15% of the world's proven oil reserves, (2) being the world's largest crude oil exporter, and (3) having the world's highest crude oil production capacity of approximately 12 million barrels per day (U.S. EIA 2021). On the other hand, the Kingdom consumed over a quarter of its total oil production to generate power (EIC 2019). Historically, energy demand has expanded fast in Saudi Arabia since the establishment of the electrical sector in the early 1970s (Soummane and Ghersi 2021). Moreover, Saudi Arabia was the 11th-largest energy consumer worldwide in 2020, utilising an anticipated ten quadrillion British thermal units of total primary energy, making it the Middle East's second-largest energy user (U.S. EIA 2021). In 2018, Saudi Arabia was the world's sixth-largest gas reserve holder, with an estimated 6 trillion cubic metres (TCM) (AlGhamdi 2020). KSA's electricity is generated primarily from oil and natural gas.

In 2016, the Kingdom launched its new development program, Saudi Vision 2030. It is a sustainable vision for the future of Saudi Arabia. The Saudi Vision 2030 puts sustainability at the centre of everything the country does, from policy formulation to investment to planning and infrastructure. The main aims of the vision are to reduce the Kingdom's dependence on oil, develop public service sectors, and diversify its economy. It is looking for life after oil.

2.2 Energy in Saudi Arabia

In 2020, the total electricity consumption in the Kingdom was 289 terawatt-hours (TWh) (WERA 2020), whereas in 2018, it reached 299.2 TWh (Soummane and Ghersi 2021). Hence, the annual energy consumption growth rate continues to rise, primarily because of population expansion. The Saudi Vision 2030 highlights the Kingdom's long-term objective of generating 70 per cent to 75 per cent of its power capacity from gas and the rest from renewables and nuclear energy (EIC 2019). Furthermore, the Saudi government aims to raise its gas production by 65 per cent from present levels to become a gas exporter by 2030 (EIC 2019). In 2020, as illustrated in Figure 2.2, Saudi Arabia generated most of its electricity from natural gas (60.7%), followed by oil (39.0%). Solar energy contributed only a minimal share of 0.3% to the country's total electricity production.

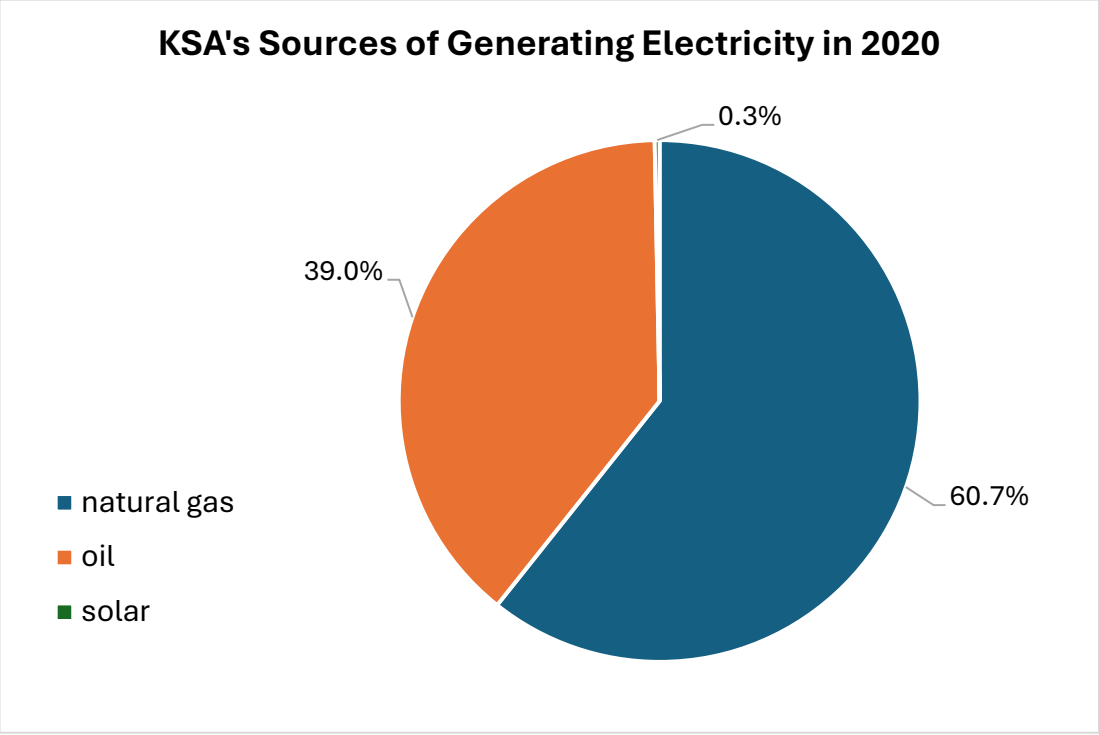


Figure 2.2.Saudi Arabia's electric power generating in 2020

Reproduced from (U.S. EIA 2021)

2.2.1 Energy Sources and Production

Saudi Electricity Company (SEC) is the leading power supplier in Saudi Arabia. The company aims to generate, transmit, and distribute electricity in the country, either directly or through totally or partially owned subsidiaries. Also, Marafiq is a private power and water utility company for Jubail and Yanbu. In addition, Marafiq supplies the two industrial cities with electricity and utility services to all the industrial, commercial, and residential communities. Table 2.1 exemplifies the two companies' peak load in 2020 and the portion of each party in September.

Table 2.1. KSA peak load and Available Capacities in 2020

reproduced from (WERA 2020)

Company name	Available Capacity (MW)	Peak Load (MW)	Reserve Margin (MW)	Peak Load Date	Peak Load Time
National Grid SA	64,818	62,266	2,552	23rd July	14:30
Marafiq (Yanbu)	1,830	1,263	567	27th Aug.	14:46

As shown in Table 2.2, the average peak load is about 62 GW in early September or late August. The minimum peak load was in 2018 with 61.7 G.W.

Table 2.2. Peak load time and consumption in KSA

source: (Benali, Ansari et al. 2020)

The Year	Peak Load Time	G.W.
2019	September 1st	62.1
2018	September 2nd	61.7
2017	August 22nd	62.1

In 2019, Saudi Arabia generated the most electricity in the Middle East, with an estimated 362 terawatt-hours (U.S. EIA 2021). However, power generation growth has slowed dramatically as population growth has slowed, GDP growth has slowed, energy efficiency and demand-side control measures have been introduced, and electricity costs have risen during 2016 and 2018 (U.S. EIA 2021).

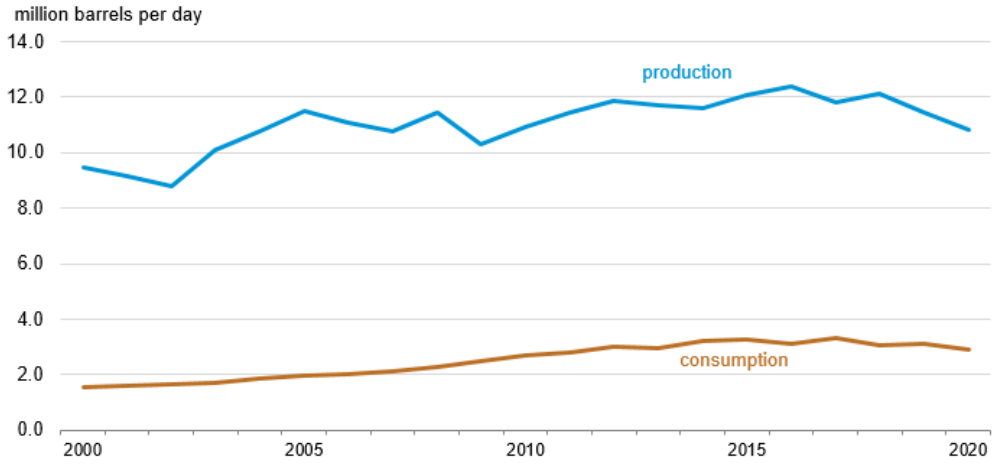


Figure 2.3. Petroleum and other liquids produced and consumed in SA (U.S. EIA 2021)

Figure 2.3 depicts Saudi Arabia's production and use of petroleum and other liquid fuels during the recent two decades. The line graph represents the production and consumption path with a million barrels daily between 2000 and 2020. The average production is about 10 to 12 million barrels per day, while the highest point was in 2016 and the lowest in 2002. For the consumption aspect, generally, it is clear that the average output is around 2 and 4 million barrels per day. For the last decade, the consumption was about a third of the production.

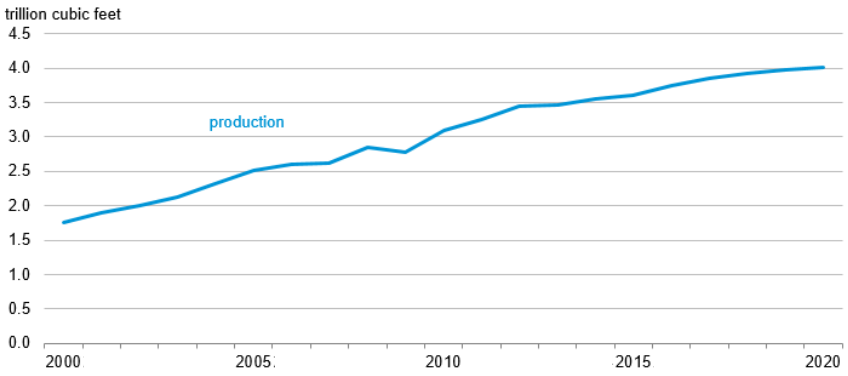


Figure 2.4. Dry natural gas production of KSA (U.S. EIA 2021)

Figure 2.4 illustrates Saudi Arabia's dry natural gas output from 2000 to 2020. The figure shows the increased natural gas production in the Kingdom for twenty consecutive years, starting in 2000. According to the (U.S. EIA 2021) report, the annual gas consumption is between 2 and 4 trillion cubic feet, equal to the domestic production over the given period. Saudi Arabia has consumed all of its natural gas produced. Indeed, Saudi Arabia imports and exports no natural gas, and its total natural gas demand is fulfilled by domestic production (U.S. EIA 2021).

2.2.2 Energy Consumption

In Saudi Arabia, power demand can be divided into two distinct phases. Phase 1 (2000–2015), which this study concentrates on, represents a period essentially lacking rules to regulate the rapid growth in energy use. The annual energy consumption growth rate was six per cent between 2000 and 2015 (U.S. EIA 2021). Conversely, Phase 2 (2015–present) is characterised by the establishment and development of new regulations and codes. When comparing the two phases, Phase 2 has introduced critical measures such as energy sales pricing, building and construction standards, and household electrical appliance regulations.

Figure 2.5 represents the total sum of the residential sector energy consumption per capita for six recent years, from 2015 to 2020. The bar chart covers the first stage of Saudi energy consumption focusing on the housing units.

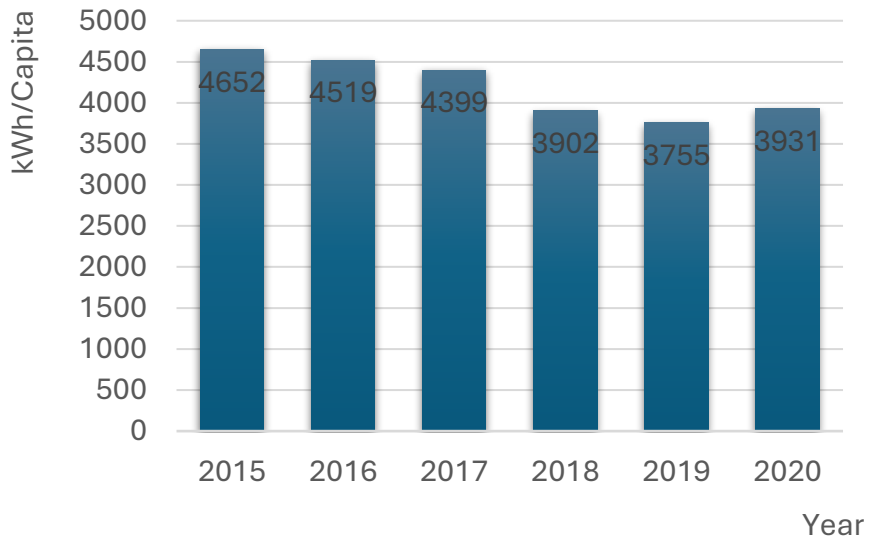


Figure 2.5. Saudi residential electricity usage per capita from 2015 to 2020

Data sources (WERA 2020) and (ECRA 2019)

Figure 2.5 depicts a decrease in electricity consumption over the given frame time with an annual average rate of 3.85 per cent till 2019 and an increase in 2020. Generally, the energy consumed in the Kingdom declined slightly between 120 kWh and 150 kWh, except for a sharp decrease of 500 kWh in 2018. Several reasons affected the continuous energy usage dropping, such as new high tariff electricity rates and regulation changes on electrical appliances. However, the energy consumption was 180 kWh higher in 2020 compared to 2019 because of the growing

customer number. In conclusion, the average annual Saudi electric power consumption per capita has been around 4200 kWh over the years.

Despite the annual decrease in the total energy consumed in Saudi Arabia, the customer number has increased due to population and development growth. Figure 2.6 shows that SEC's consumers increased among all sectors from 2015 to 2019. The chart illustrates the rapidly raised number of customers from about eight thousand to almost ten thousand for all categories.

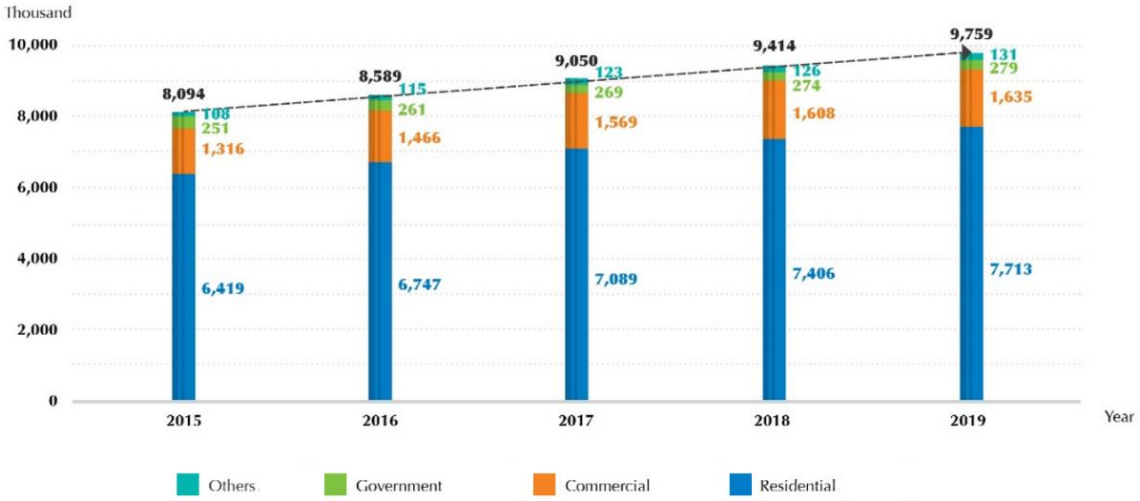


Figure 2.6. SEC Customer number for different sectors (ECRA 2019)

In addition, Figure 2.6 addressed a substantial proportion of the residential sector compared to others. In 2019, the number of residential customers was about 7800, two-thirds of the total consumer. The commercial industry came second with no comparison to the residential sector, followed by the government sector, 1635 and 279 respectively.

Table 2.3. Saudi Customers and Energy Sales (GWh) in 2020 source (WERA, 2020)

	Saudi Electricity Company (SEC)		Marafiq (Yanbu)		Total Percentage	
Category	Number of Customers	Energy Sales (GWh)	Number of Customers	Energy Sales (GWh)	Customers %	Energy Sales %
Residential	8,047,072	137,275	14,920	378	79.5	47.6
Commercial	1,659,484	40,977	1,397	94	16.4	14.2
Government	281,841	35,957	3,076	233	2.8	12.5
Industrial	12,214	50,762	121	7,118	0.1	20
Others	122,284	15,840	22	699	1.2	5.7
Total	10,122,895	280,811	19,536	8,522	100	100

Table 2.3 illustrates the energy sales and customers number in Saudi Arabia from both power companies, SEC and Marafiq, in 2020. The residential, industrial, and commercial energy usage percentages are 47.6%, 20%, and 14.2%, respectively.

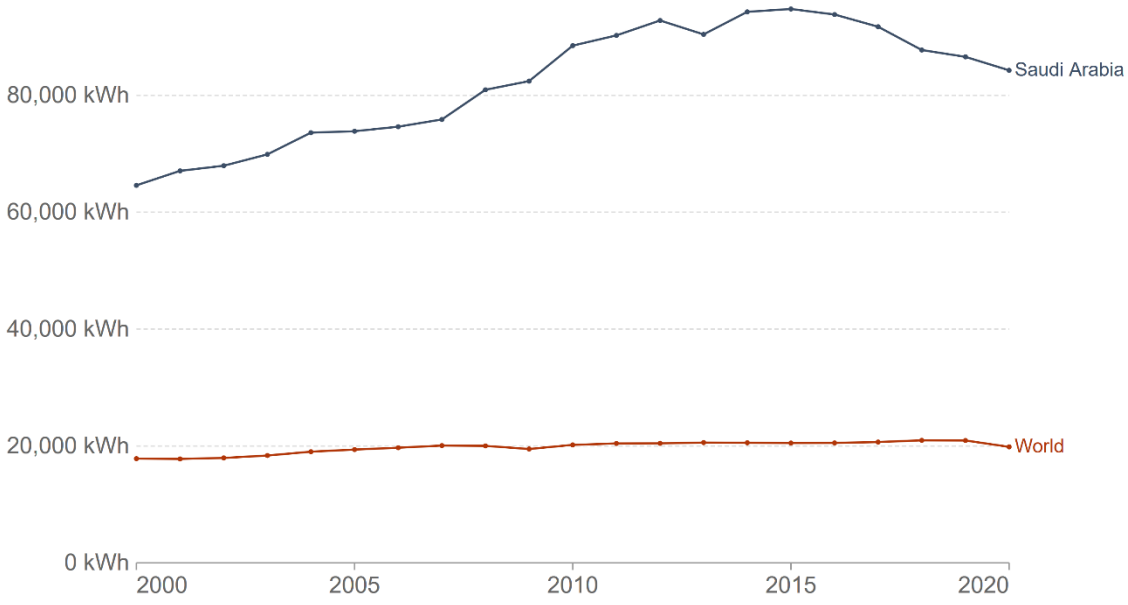


Figure 2.7. KSA and global per capita energy consumption from 2000 to 2020 source: (Ritchie, Roser et al. 2020)

Figure 2.7 presents Saudi Arabia's per capita energy consumption between 2000 and 2019. The energy usage includes electricity and other use areas such as transportation, cooking, and heating. As illustrated in the figure, Saudi per capita energy consumption has increased significantly over the years. While the average world energy demand per capita was steady at around 20 thousand kWh over the

given frame time, KSA energy demand showed different scenarios. First, consumption increased rapidly for ten years, starting in 2000. Then, energy usage keeps fluctuating for five years. Finally, it declined slightly to 90 thousand in 2019. Generally, the Saudi per capita energy consumption has overgrown in the given years, and it is now more than four times the global average.

Three main sectors, including industry, construction, and transportation, absorb 90% of the Kingdom of Saudi Arabia's domestic energy consumption (SEEC 2021). The Saudi building sector has three types: residential, governmental, and commercial. This building sector consumption exceeded 75% of total electric energy produced in the Kingdom, with an annual increase rate of roughly 5% (SEEC 2021). The residential sector is one of the noticeable sectors concerned with reducing electricity power usage.

Air conditioning (AC) is a significant global element for most interior environments. It keeps the thermal comfort zone under control. According to KAPSARC, 1.6 billion AC devices operate worldwide, requiring over 2,000 terawatt-hours (TWh) of power annually. Saudi Arabia is the world's third-largest electricity consumer for air conditioning behind the United States and China; it accounts for 10% of the total cooling demand among G20 countries (Alshehri, Howarth et al. 2020). However, domestic energy reform and stricter AC energy efficiency regulations have resulted in less oil being burned to keep cool. Although third in total volume, Saudi Arabia has the world's highest proportional AC use; cooling accounts for over half of building electricity, representing 101 TWh (residential) and 70 TWh (commercial) in 2018 (Alshehri, Howarth et al. 2020).

Moreover, residential buildings consume excessive electrical energy, particularly during the summer when air conditioning (AC) accounts for most energy usage. As stated by (Alshehri, Howarth et al. 2020), 'Saudi Arabian households have the world's highest share of AC consumption from electricity demand at around 70% of total residential electricity consumption.' Due to the high temperature in most cities in Saudi Arabia, the need for air cooling systems stands for most of the consumption. In addition to the energy increased consumption, the quick expansion of air conditioning usage in buildings has various downsides, including (1) issues of indoor air quality, (2) rises peak power demand, and (3) environmental difficulties, for example, ozone layer depletion and global warming (Alaidroos and Krarti 2016).

Figure 2.8 chart shows the energy consumed in Saudi Arabia between 2000 and 2015. In general, energy usage has risen over time. For example, it can be witnessed from Figure 2.8 that, in 2015, the energy demand kept growing till it reached the peak of 285 (TWh). After that, the direction kept increasing rapidly by about 4 per cent yearly. Several factors have caused this rapid increase in total energy, including a growing population, low tariff power rates, and dynamic economic expansion.

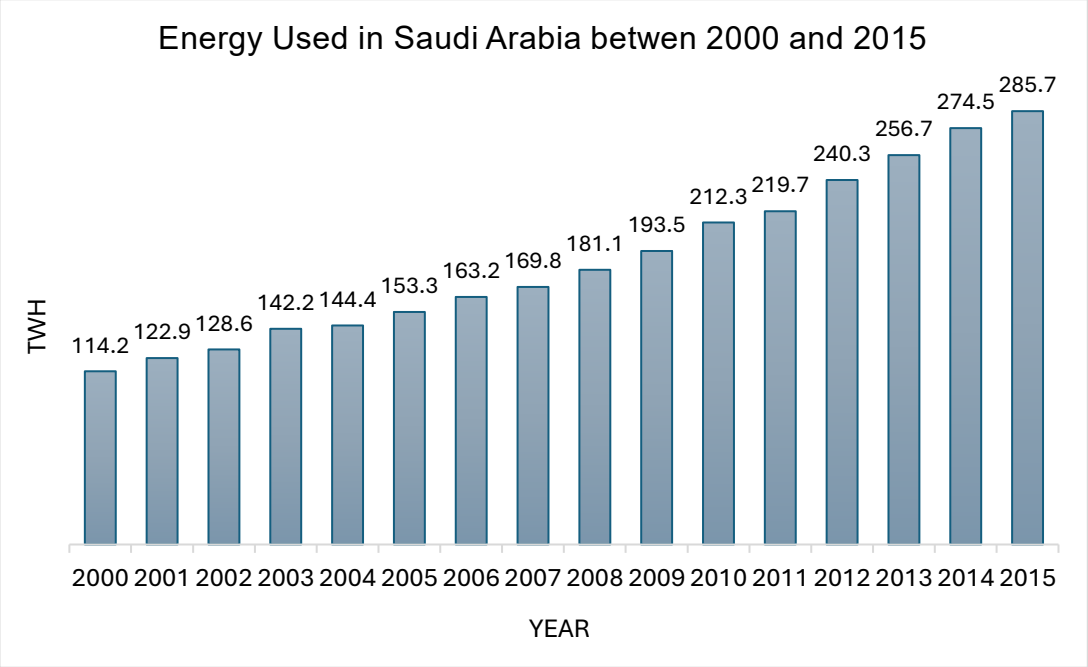


Figure 2.8. Energy Used (TWh) in KSA from 2000 to 2015 (SEC 2021)

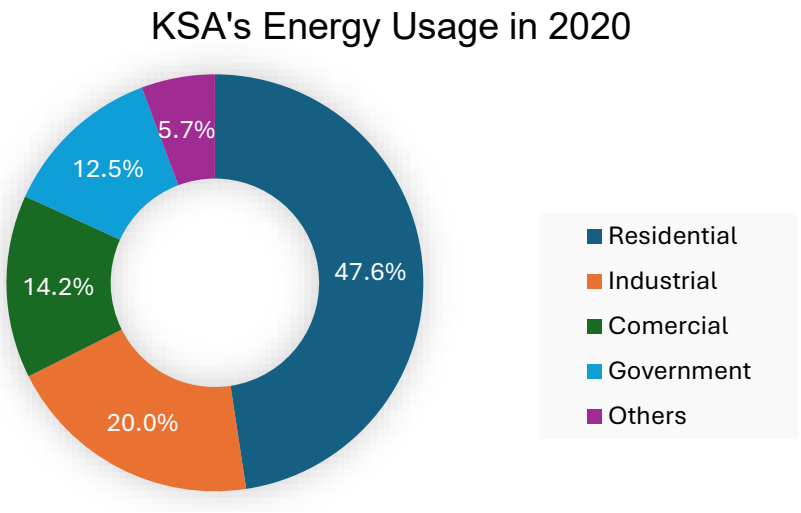


Figure 2.9. Saudi Arabia Energy Usage in 2020 source (WERA 2020)

Figure 2.9 illustrates the proportion of electricity usage for several sectors in Saudi Arabia in 2020. The residential sector accounts for substantial energy consumption.

The residential sector consumed almost half of the generating energy with 47.6 per cent. In comparison, the industrial sector demand came second, followed by the commercial sector with 20 per cent and 14.2 per cent, respectively.

The Saudi Electrical Company defines peak time as when the electrical loads are at their highest level. In KSA, the seasonal peak spans typically from late August to early September. During the summer, the peak load period occurs on weekdays, Sunday to Thursday, between 2:00 p.m. and 2:30 p.m. (Benali, Ansari et al. 2020).

2.3 Sustainability Status of Saudi Building Sector

As (Alulayet, Panuwatwanich et al. 2012) said, using sustainability to minimise conventional electricity consumption in the building sector will reduce reliance on such non-renewable resources as energy sources for buildings. It also gradually shifts toward greater reliance on alternative renewable energy sources, like solar and wind (Alulayet, Panuwatwanich et al. 2012). Saudi Arabia is one of the developing countries undergoing rapid urbanisation, and its infrastructure is under increasing pressure as the population of its major cities grows.

As (Alrashed and Asif 2012) defined the building's construction for previous and current times: 'In the past, buildings constructed from local materials that were produced in-situ such as limestone, coral, stone and wood. Traditional homes are made from thick walls and roofs for better thermal insulation. In contrast, new buildings are described as modern homes made of reinforced concrete with thin walls and ceilings (Alrashed and Asif 2012). Most homes lack effective insulation, and many are not insulated because there is no financial incentive or legal obligation to conserve energy (Aluwaisheg 2013).

Developing sustainable housing in Saudi Arabia is essential to preserve resources for future generations in the country and the world (Al Surf, Susilawati et al. 2014). There are two causes of energy overconsumption in Saudi Arabia, according to (Aluwaisheg 2013); including the legislation governing building cooling systems is set to deficient standards, which results in excessive energy use. The second reason is that there are no tight requirements for builders to employ a specific type of insulation, which helps to reduce overall energy consumption drastically.

2.3.1 Development of Saudi Sustainable Buildings

In Saudi Arabia, sustainable development is relatively new. The term was first recognised through King Abdullah's initiative in 2010 when the only sustainable project was King Abdulla University of Science and Technology (KAUST) (Al Surf 2014). The KAUST campus project received Leadership in Energy and Environmental Design (LEED)-Platinum certification.

First sustainable project in the Kingdom

The KAUST campus is the first green project in Saudi Arabia, which is located in Thuwal village in the western region of the Kingdom. The total project area is 5.5 million square feet. The development of this project shows that the government builds this substantial green project to create sustainability. According to (Landreneau 2014), the KAUST campus was the first project to achieve LEED certification in the Kingdom, and in 2009 it was the largest LEED Platinum-certified project globally. The government company Saudi Aramco is managing the project. The Saudi government requested that HOK (a multinational design, architecture, engineering, and planning firm) design the project. The success of building the campus demonstrates the government's commitment to saving energy for future generations.

Second sustainable project in the Kingdom

The second green project is a residential community for the King Abdullah Petroleum Studies and Research Center (KAPSARC). In 2009, a complex of 82 villas was built, also designed by the HOK. The villas project achieved LEED Gold certification. It is the most significant and first housing development to receive LEED residential building certification outside North America (Landreneau 2014).

The Saudi government's sustainable movement

The previous examples are the first steps towards sustainable living. According to Faisal Al-Fadl, the secretary-general of the Saudi Green Building Forum (SGBF), the number of sustainable and green developments increased to 140 projects in 2013, 40 of which are located in Riyadh, the city capital of the Kingdom (Rasooldeen 2013). According to an analysis of the construction industry, most projects in Saudi Arabia are residential developments to accommodate the demand for new dwellings (Alrashed and Asif 2014).

Furthermore, the Saudi government expanded the use of gas instead of oil due to the high energy demand of its producing power, which has developed the use of efficient gas plants (Soummane and Ghersi 2021). The change helps reduce the need for oil to generate electricity. In addition, as (Soummane and Ghersi 2021) stated, policymakers in Saudi Arabia have also implemented specific requirement policies to support its energy efficiency path, such as:

1. In 2010, the establishment of the Saudi Energy Efficiency Center (SEEC)
2. In 2016, the energy consumption tariff increased, with following raised in 2018
3. In mid-2021, applying the Saudi Building Code to the residential sector

These several steps have been taken to reduce energy consumption and increase efficiency, primarily for the residential sector.

2.3.2 Saudi Government Rules, Regulations, and Guidelines

An overview of the regulations in the Kingdom

In Saudi Arabia, the Ministry of Municipal, Rural Affairs, and Housing (MOMRA) is responsible for the Saudi Building Code National Committee (SBCNC). In 2007, SBCNC published the first Saudi Building Code (SBC), issuing only the architectural part. The national committee described the SBC as a combination of legal, administrative, and technical laws and procedures determining the minimum construction standards for buildings to ensure public safety and health (SBCNC 2007). The International Code Council (ICC) is the base code for the Saudi Building Code, which was chosen after comprehensive studies of various international regulations around the globe, such as the USA, Australia, Canada, Europe, and Arab building codes. Also, several specialised workshops and meetings took place through both the government and private sectors in Saudi Arabia (SBCNC 2007). In July 2021, Saudi Building Code became required for all residential buildings in the Kingdom. The SBC has 18 categories covering all designing and construction aspects. This research study covers just sustainability aspects of the SBC, such as the Residential Energy Conservation Code - SBC 602, because of its focus on the residential energy aspect.

The Saudi Energy Conservation Code (SBC 602)

Saudi Energy Efficiency Center (SEEC) established the Saudi Energy Conservation Code (SBC 602) under the direction of the SBCNC (SBC 602 2018). The Saudi Energy Conservation Code (SBC 602) establishes minimum energy efficiency requirements for low-rise residential buildings in the Kingdom. As defined by (SBC 602 2018), basic standards of design and construction for energy-efficient in the code applies to

1) New residential dwelling units and their systems
2) Where explicitly specified
    i) New systems and devices for existing housing units
    ii) Additional portions for a residential housing unit and its systems

SBC 602 addresses energy efficiency requirements for energy use in residential buildings, such as ventilation and heating, hot water production, lighting, and electricity consumption by appliances and building systems. The residential dwelling units covered in this code are single-family houses, multi-family structures (of three stories or fewer above grade), and modular houses (SBC 602 2018). SBC 602 covers minimum requirements for enclosure insulation, U-Factors and SHGC ratings for doors

and windows, duct insulation, lighting and energy efficiency, and water distribution insulation.

In the SBC 602, all the standard obligations related to the envelop are summarized in Table 2.4 for each Saudi climate zone. The SBC has only three climatic zones for the whole country. The main elements to acquire the model to meet the SBC 602 starting with the envelope including wall, roof, and window. At Zone 1, a U-Value of 0.342 W/m²·K is the maximum obligation for wall. This results in a required insulation thickness of approximately 5.6 cm for the climate of Madinah (sometimes spelled Medina). This insuring the requirement is met. Windows must have a maximum U-value of 2.668 W/m²·K, with flexibility of WWR not to exceed 25%. 0.202 W/m²·K for the exterior roof. The airtightness is 4.0 at ACH50.

Table 2.4. Saudi Building Code summary

Standard	Climatic zone	U-Value W/(m²·K)			
		Wall	Roof	Window	Door
SBC 602	Zone One	0.342	0.202	2.668	2.839
	Zone Two	0.397	0.238	2.668	2.839
	Zone Three	0.453	0.273	2.668	2.839

Indeed, it is essential to adopt a passive house standard like the Passivhaus to the residential building sector in Saudi Arabia. However, there is no official authority yet to lead the way in adopting the Passivhaus standard in the Kingdom.

2.4 Previous Literature Findings

Literature indicates a consensus regarding the excessive energy consumption of the residential sector in the Kingdom of Saudi Arabia (KSA) (Ahmed, Asif et al. 2019). Domestic buildings account for approximately half of the national electricity expenditure, driven by a reliance on mechanical cooling and inefficient construction practices; notably, up to 70% of dwellings lack adequate thermal insulation (Alshenaif 2015, Abuhussain 2020). Although the Saudi Building Code (SBC) mandates minimum thermal performance standards, a significant disconnect remains between its regulatory framework and practical implementation (Alyami 2022). Studies identify a lack of stakeholder awareness, insufficient legislative enforcement, and a failure to align the code with current industry capabilities (Al Surf 2014, Abuhussain 2020). To address this regulatory gap, this research establishes an empirical baseline by examining the Saudi Energy Conservation Code (SBC 602), quantifying the energy performance of compliant dwellings to assess the code's practical efficacy.

To advance building performance beyond baseline regulations, literature extensively examines the Passivhaus standard. Originating in Germany in the early 1990s, it is globally recognised as a rigorous framework for achieving ultra-low energy consumption (Lynch 2014, Vettorazzi, Figueiredo et al. 2021). Its five fundamental principles comprise high thermal insulation, extreme envelope airtightness, high-performance windows, mechanical ventilation with heat recovery (MVHR), and the minimisation of thermal bridges (Khalfan 2017, Kang, Chang et al. 2021). Adherence to these principles mandates stringent benchmarks, notably a maximum space heating and cooling demand of 15 kWh/(m²a) and an airtightness limit of 0.6 air changes per hour at 50 Pascals (Khalfan, Sharples et al. 2015, Vettorazzi, Figueiredo et al. 2021). In cold and temperate European contexts, such as the CEPHEUS project, Passivhaus implementation has successfully reduced operational energy demand by 80% to 90% compared to conventional construction (Lynch 2014, Liu 2021).

Despite its documented success in Central and Northern Europe, researchers critically evaluate the standard's geographical transferability (Khalfan and Sharples 2016, Echarri-Iribarren, Sotos-Solano et al. 2019). Investigations into its application within warmer Mediterranean and subtropical climates confirm its potential for energy savings but consistently highlight a severe risk of prolonged summer overheating (Alshenaif 2015, Kang, Chang et al. 2021). Consequently, scholars caution that directly transferring European specifications to hotter climates without rigorous

climatic harmonisation compromises indoor thermal comfort and inflates cooling demands (Khalfan 2017, Echarri-Iribarren, Sotos-Solano et al. 2019).

Accordingly, recent literature focuses on adapting these principles to extreme hot and arid climates, particularly within the Gulf Cooperation Council (GCC) region. Empirical evidence from the first Passivhaus pilot project in Qatar demonstrates both its viability and limitations. Although the Qatari dwelling reduced annual operational energy and cooling demands by over 50% compared to an adjacent conventional villa (Khalfan, Sharples et al. 2015, Khalfan 2019), it initially failed to meet the stringent German primary energy benchmarks. Ultimately, integrating solar renewable technologies was necessary to offset the substantial, continuous cooling loads inherent to the region (Alshenaif 2015, Khalfan and Sharples 2016).

While the Passivhaus framework offers an effective pathway to optimise building energy performance, its core parameters require fundamental revision for extreme Middle Eastern climates (Alshenaif 2015). To minimise cooling loads and prevent overheating, studies advocate for region-specific optimisation of the thermal envelope, necessitating bespoke insulation thresholds, context-specific ventilation strategies, and carefully calibrated window-to-wall ratios (Liu 2021, Alyami 2022). Addressing these empirical warnings and existing geographical gaps, this study tests the feasibility of the Passivhaus standard across the diverse climatic zones of Saudi Arabia, determining the requisite envelope adaptations. Methodologically, evaluating low-energy buildings demands dynamic Building Performance Simulation (BPS) to account for regional climatic variations (Ahmed, Asif et al. 2019). Previous Saudi-based investigations predominantly relied on isolated parametric assessments or single-city case studies, neglecting the Kingdom's climatic diversity (Alosaimi 2023). This research overcomes such limitations through a holistic, multi-region evaluation using dynamic BPS. By benchmarking an adapted Passivhaus standard against SBC 602 requirements across varied Saudi climates, this study provides robust, region-specific guidance to optimise performance-based sustainable building standards.

2.5 The Research Gap

While the need for sustainability in the Saudi built environment is widely recognised, existing research has primarily focused on partial or incremental efficiency improvements. For instance, previous studies investigating sustainable approaches in the Saudi building sector, such as those by (Alaidroos and Krarti 2015), (Alshaikh 2016), (Ahmed, Asif et al. 2019), and (Al-Tamimi 2021), have sought to enhance residential energy performance through sensitivity analyses and the optimisation of building envelopes. However, these publications have not comprehensively examined the Passivhaus standard within the context of this thesis.

Consequently, empirical research regarding the Passivhaus standard in the Kingdom remains limited. Specifically, there is an absence of studies examining its application within residential flats across the country's complete climatic context. This presents an essential opportunity to investigate the standard's applicability in the Kingdom of Saudi Arabia and to evaluate its potential environmental benefits.

The measurable research gap lies in the lack of empirical, simulation-based data quantifying the differences in energy performance measures among conventional Saudi construction, the implemented Saudi Building Code (focusing on SBC 602), and a fully adapted Passivhaus standard. Furthermore, existing literature has not yet quantified the optimal window-to-wall ratios (WWR), thermal envelope U-values, and airtightness parameters required to meet Passivhaus criteria across the five distinct climatic zones of the Kingdom.

This research bridges this gap by directly measuring and comparing the energy consumption outcomes of these three standards, baseline, SBC, and Passivhaus, across five representative Saudi cities, providing a quantifiable, evidence-based pathway for sustainable residential development.

3 CLIMATIC ZONING AND ENERGY INDICATORS

3.1 Introduction

The local climate substantially impacts the design and functioning of buildings. As shown in Table 3.1, Saudi Arabia is divided into thirteen regions, the most populated of which are Makkah, Riyadh, Eastern Province, Aseer, and Madinah, with the most housing units in 2019. While Aseer is the highest region at 22,228 metres above sea level, Eastern Province is only 10 metres above sea level.

Table 3.1 Regions of Saudi Arabia

No	Region Name	Capital City	Elevation (m)	Region Population	Housing Units
1	Ar Riyadh	Riyadh	612	8,591,748	3,123,246
2	Makkah Al Mukarramah	Mecca	333	8,021,463	3,260,806
3	Eastern Province	Dammam	10	5,125,254	1,902,754
4	Al Madinah Al Munawwarah	Medina	603	2,137,983	843,660
5	Aseer	Abha	2,228	2,024,285	893,307
6	Jazan	Jizan	19	1,404,997	481,663
7	Al Qaseem	Buraydah	606	1,336,179	538,133
8	Tabuk	Tabuk	768	886,036	352,464
9	Hail	Hail	1,002	746,406	302,895
10	Al Jawf	Sakaka	689	595,822	190,336
11	Najran	Najran	1,310	592,300	217,768
12	Northern Borders	Arar	555	373,577	108,485
13	Al Bahah	Al Baha	2,176	339,174	199,179
	Total			32,175,224	12,414,696

**Data sources: The Saudi Census 2022 and meteoblue*

Similar house designs can be spotted in Saudi mountain cities such as Abha and Al Taif. An identical dwelling is also built in the middle of the desert, such as in Riyadh. Figure 3.1 is a map of Saudi Arabia depicting the variety of the country's elevations and the Saudi regions. In addition, the map includes major Saudi cities such as Riyadh, Dammam, Madinah, Makkah, and Abha.

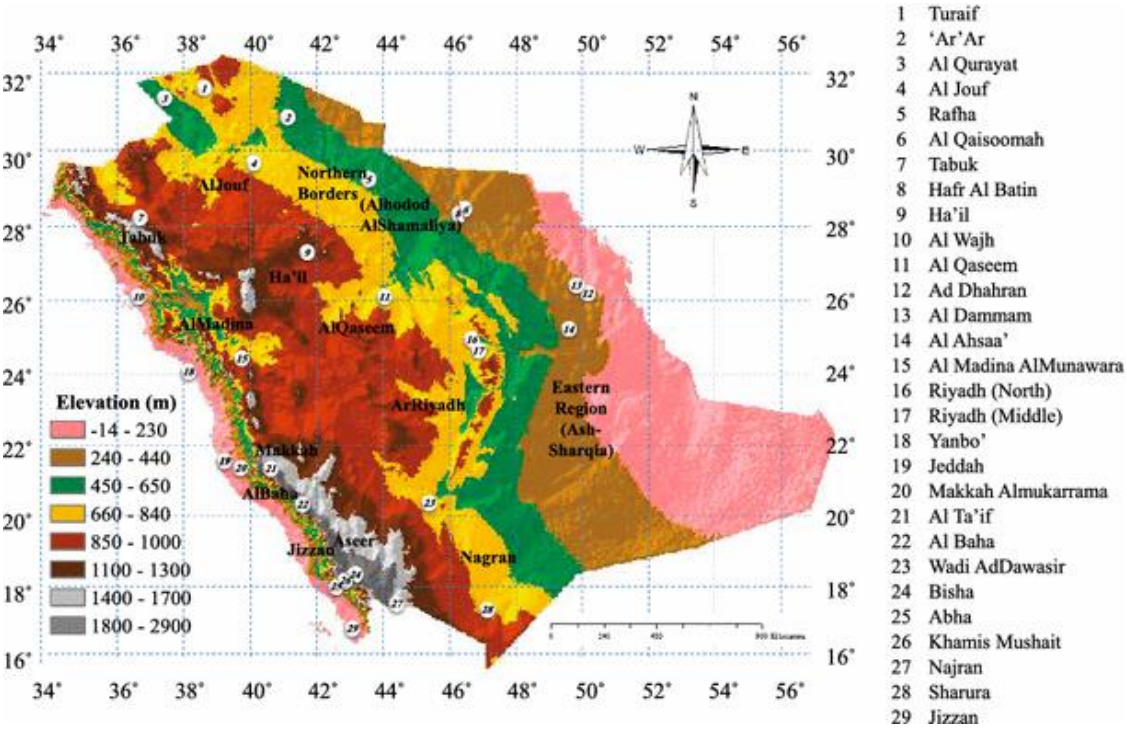


Figure 3.1. Elevation of Saudi Arabia and Weather Stations Map (Amin, Mahmoud et al. 2016)

3.2 Climatic Literature Review

Throughout the years, scientific and administrative entities have categorised Saudi Arabia as a distinct entity within the Gulf Cooperation Council (GCC) Countries, a member of the Arab World, and a part of the Middle East and North Africa (MENA) region (Alrashed and Asif 2014). The Köppen climate classification represents one of the most broadly used climate zone classification systems. The system was created by the climatologist Wladimir Koppen in 1884; it has undergone various revisions and modifications over the years but has been used by scholars worldwide (UK Met Office 2022). Figure 3.2 illustrates that the Köppen-Geiger approach classifies climate into five basic categories and thirty subtypes. The classification is based on seasonality, monthly air temperature, and precipitation threshold levels (Beck, Zimmermann et al. 2018). For example, according to the Köppen climate classification, Saudi Arabia is classified as a desert or arid climate under the hot desert climate (BWH) (Hasanean and Almazroui 2015).

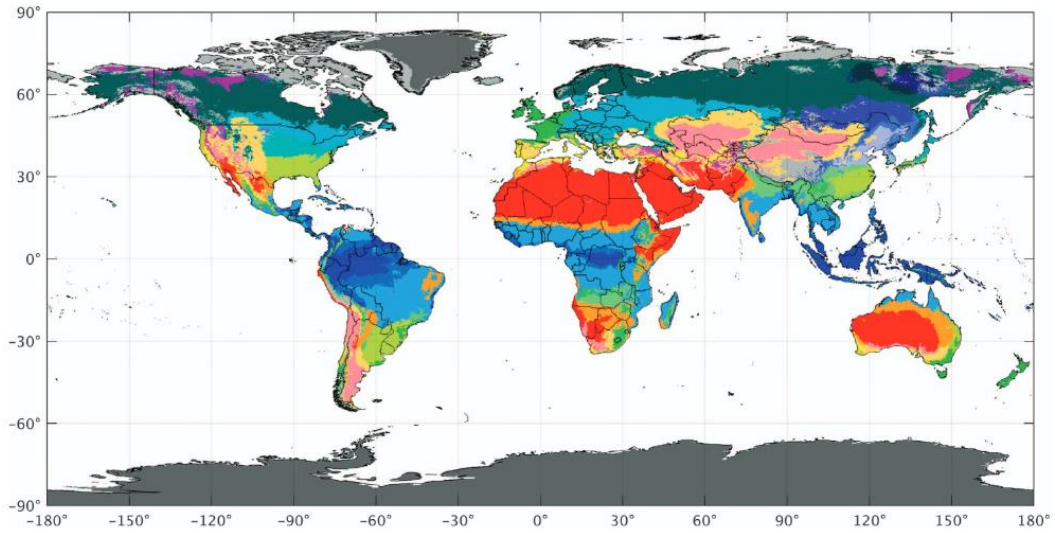


Figure 3.2. The Köppen-Geiger climate classification map from 1980 to 2016 (Beck, Zimmermann et al. 2018)

Indeed, the system lacks categorising the country as one zone. 'The building industry uses two main climate classifications: the Koppen-Gieger Climate Classification and the International Code Council (ICC) / American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) climate zones' (Ladybug Tools Academy nd). Saudi Arabia's climate has been classified in various ways by researchers and Saudi authorities, such as (SBC 602 2018), (Alrashed and Asif 2014), (Said, Habib et al. 2003), and (Al-Hadhrami 2013).

Climate challenges are one of the main issues facing architects and builders when designing and building sustainable housing in Saudi Arabia. The climate of Saudi Arabia is characterised by a semi-arid to dry desert climate with hot days and cold nights and a substantial decline in yearly precipitation. This climate causes ecological challenges, as high temperatures range from -11 °C to 51.1 °C (Susilawati and Al Surf 2011). However, the Asir region in the southwestern parts of the Kingdom receives an average rainfall of about 300 mm annually, as reported by the National Center for Meteorology (NCM) in Saudi Arabia. The climate in the country has significant temperature fluctuations between regions and cities, particularly between day and night. According to the Saudi NCM, the maximum temperature can reach 50 °C on a summer day while dropping to a minimum of 2 °C on a winter night. In Saudi Arabia, the annual average temperature is about 26 °C. Differences in high temperatures outside buildings during summer increase the demand for cooling systems. In winter, it is essential to keep your house warm. Building sustainable homes in KSA differs from other developing countries due to weather conditions.

Figure 3.3 illustrates monthly temperatures in Saudi Arabia, including the minimum, the maximum, and the mean for twenty years starting in 1991. The mean-minimum temperature is about 15° C, and the mean-maximum temperature is around 32° C. It can be clearly seen that the lowest winter temperature point took place in January, while the peak point of the summer temperature appeared in August. Also, the maximum seasonal temperature across the country is as follows: (1) 10-22°C during winter from December to February, (2) 15-37°C during spring from March to May, (3) 25-40°C during summer from June to August, and (4) 15- 38°C during autumn from September to November.

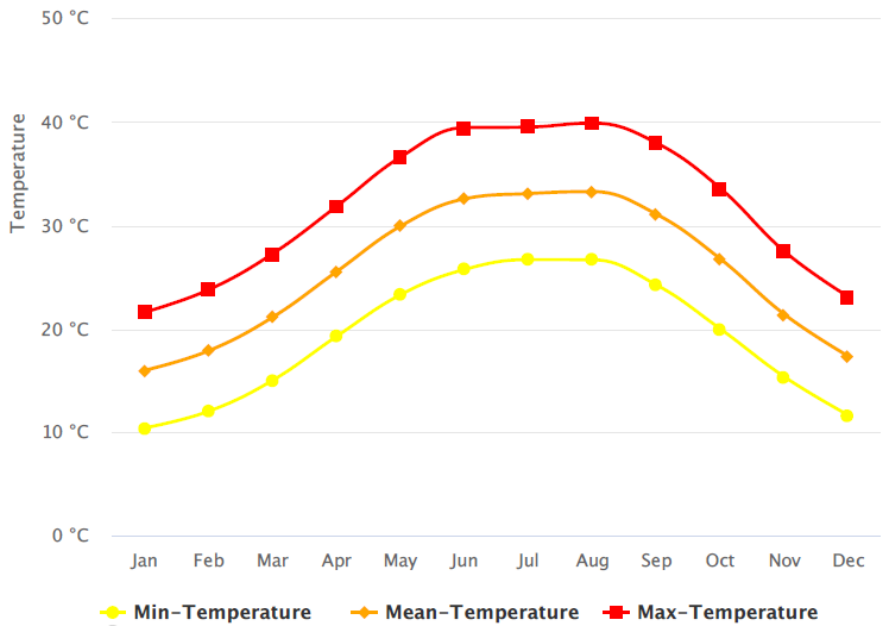


Figure 3.3. Monthly Temperatures of SA from 1991 to 2020 (World Bank 2021)

According to the KAPSARC, Saudi Arabia is located in a global warming hotspot. Over the last 40 years, the temperature in Riyadh and many other cities have increased by more than 3 degrees Celsius (°C) (Alshehri, Howarth et al. 2020).

The Saudi Building Code (SBC) is a set of comprehensive codes and standards for building design, construction, and operation in Saudi Arabia. The primary purpose of the SBC is to establish minimum requirements, investigate public health and safety through the stability of buildings and facilities, and safeguard life and property from building-related dangers (Dahish, Almutairi et al. 2020). As shown in Figure 3.4, Saudi Building Code (SBC 602) divided the Kingdom of Saudi Arabia into three climate zones. The categories of the three zones are based on the International Energy Conservation Code (IECC), which the IECC code specifies best practices for energy efficiency. Zone 1 encompasses the majority of Saudi Arabia, while Zone 3 is the smallest and coldest.

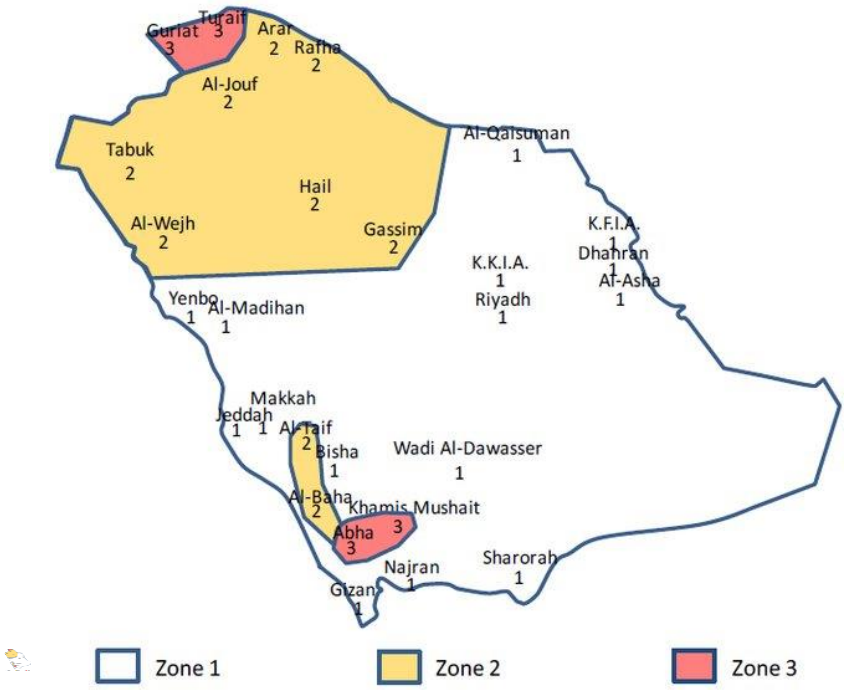


Figure 3.4. Building Code climatic Zones in SA source: (SBC 602 2018)

Several researchers have contributed to the development of the Saudi climatic zoning such as the map produced by (Alrashed and Asif 2014), who used the primary climate zone data introduced by (Said, Habib et al. 2003), which zoning category proposed originally in (Said, Kadry et al. 1996).

Figure 3.5 illustrates the climatic data for five different zones of Saudi Arabia and five cities worldwide with similar climates. The table focuses on four climate aspects to show accurate analysis. According to the study, Dhahran is the hottest city, Guriat is the coldest, with 45.7 and -3.3 degrees Celsius, respectively, while Jeddah has the most significant humidity at 64.7 per cent.

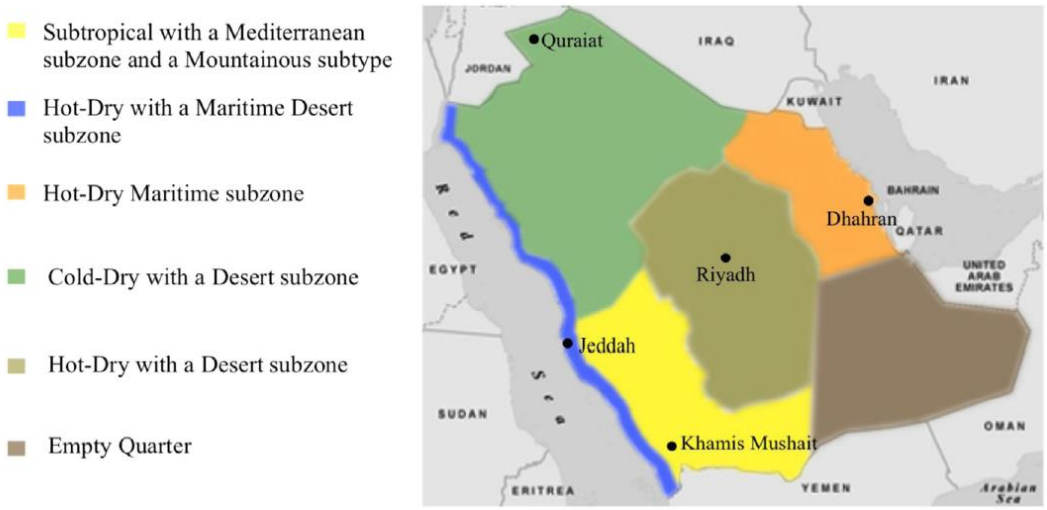


Figure 3.5 Saudi Arabia's Climatic Zones (Alrashed and Asif 2014)

A paper by (Al-Hadhrami 2013) reviewed CDDs and HDDs in Saudi Arabia. Figure 3.6 shows suggested zones based on CDDs for Saudi Arabia. A map was created using updated data. The zones have two fundamentals: first, they have a weather station, and second, they are categorised by similar annual CDDs. Zone 1 is the hottest area which demands more cooling; however, Zone 4 is the coldest zone which requires heating rather than cooling.

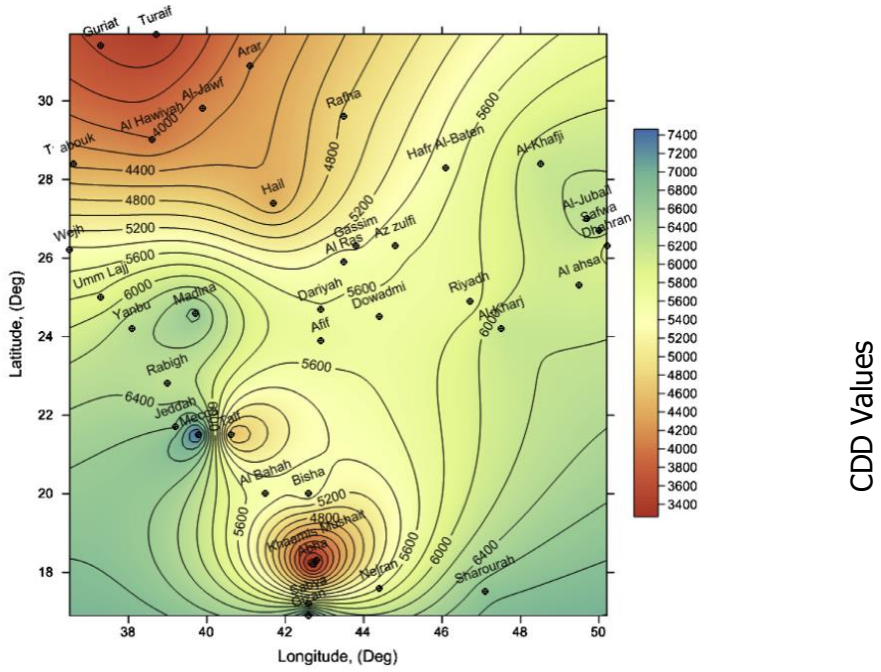


Figure 3.6. Saudi Arabia Contouring Map of CDD (Al-Hadhrami 2013)

Indeed, the discrepancies in the previous climate zoning studies and standards led to the need for deeper research.

3.3 Materials and Methods

3.3.1 Climatic Zoning Parameters

There are several methods to develop climate zoning for a country, which apply to Saudi Arabia. Recent research examined the climatic zoning methodologies utilised for building energy efficiency programmes in 54 countries., with 80% of these countries defining their climatic zoning using only up to three techniques and variables (Walsh, Cóstola et al. 2017). Furthermore, 19 climatic zoning parameters were discovered, with degree days, temperature, relative humidity, administrative divisions, and height being the most frequently employed (Walsh, Cóstola et al. 2017). In a study by (Büyükalaca, Bulut et al. 2001), long-term and recently-measured data are used to calculate Turkey's heating and cooling degree days. In Oman, for instance, research estimated the CDD and HDD for 31 weather stations in the country to generate a map of Oman-specific climate classification (Al-Saadi, Al-Rawas et al. 2022).

In this study, three methods have been chosen to develop a climate classification zoning for Saudi Arabia, which included mainly the degree days method and modified the zoning borders using temperature and relative humidity. Indeed, the paper analyses climate parameters of temperature and humidity data to determine the feasibility of better-classifying zoning in Saudi Arabia.

3.3.2 Degree Days Method

The Degree-day approach is a widely recognised technique developed during the 1920s for estimating the monthly and annual cooling and heating needs of specific buildings in various locations (Said 1992). The degree day method is a technique used to estimate the heating or cooling required to maintain a comfortable indoor temperature in a building. The method involves comparing the average daily outdoor temperature to a base temperature, which depends on the location. According to Said, 'The base temperature should equal the building's temperature, defined as the temperature below or above which the heating or cooling system is needed' (Said 1992). 'The balance temperature for a building is the outdoor temperature at which neither heating nor cooling is required' (Al-Homoud 1998). In particular, (Harvey 2020) presented a comprehensive review of the base temperatures utilised for calculating CDD and HDD for several countries worldwide. For instance, 18.3 °C (65 °F) is typically the base temperature in the USA (Lee, Baek et al. 2014). Also, degree days are reported monthly for 18 regions in the United Kingdom, using a standard base temperature of 15.5 °C (CIBSE 2006). However, the base temperature also differs between heating degree days and gets higher temperatures for cooling degree days. Degree days measure how far daily average temperatures deviate from their base value.

The degree-day approach is frequently used in calculating building energy consumption. Cooling degree day (CDD) is a measurement for calculating the energy needed to cool buildings. In addition, Heating Degree Day (HDD) determines the energy required to heat a building. In hot weather, Cooling Degree Days indicate the energy consumed for cooling; Heating Degree Days indicate the energy consumed for heating in cold weather. The calculation of CDD and HDD with the necessary equations is well explained in the literature review provided by (Büyükalaca, Bulut et al. 2001) and (Al-Saadi, Al-Rawas et al. 2022). In 2006, The Chartered Institution of Building Services Engineers, UK, published the updated TM 41 Degree-days: Theory and Application (CIBSE 2006).

3.3.3 Meteorological Data and Degree Days Calculation

This study used high-quality and accurate meteorological data from local Saudi weather stations with a maximum annual of 0.3% for estimating the missing ones. In addition, recent climatic data for 2017 through 2021 have been utilised. Figure 3.7 shows the location of metrological stations in Saudi Arabia. In addition, Table 3.2 illustrates detailed information on the selected 21 Saudi Arabian meteorological stations used for climate data.



Figure 3.7 Metrological Stations in Saudi Arabia

Table 3.2. Selected Saudi Weather Stations

No.	Station ID	Region	Station Location	latitude	longitude
1	OEGT	Al Jouf	Guriat	31.41N	37.28E
2	OERR	Northern Border	Arar	30.91N	41.14E
3	OESK	Al Jouf	Sakaka	29.79N	40.10E
4	OETB	Tabuk	Tabuk	28.38N	36.60E
5	OEHL	Hail	Hail	27.44N	41.69E
6	OEDF	Eastern Province	Dammam (KFIA)	26.43N	49.80E
7	OEGS	Al Gassim	Buraidah	26.30N	43.77E
8	OEWJ	Tabuk	Al Wejh	26.20N	36.48E
9	OERK	Al Riyadh	Riyadh (KKIA)	24.71N	46.73E
10	OEWD	Al Riyadh	Wadi Al Dawasser	24.71N	46.73E
11	OEMA	Al Madinah	Madinah	24.55N	39.71E
12	OEYN	Al Madinah	Yanbu	24.14N	38.06E
13	OEJN	Makkah	Jeddah	21.70N	39.18E
14	OETF	Makkah	Al Taif	21.48N	40.54E
15	OEBA	Al Baha	Al Baha	20.30N	41.63E
16	OEBH	Aseer	Bisha	19.98N	42.62E
17	OEKM	Aseer	Khamis Mushait	18.30N	42.80E
18	OEAB	Aseer	Abha	18.24N	42.66E
19	OENG	Najran	Najran	17.61N	44.42E
20	OESH	Najran	Sharurah	17.47N	47.12E
21	OEGN	Jazan	Jizan	16.90N	42.59E

Based on the integrated method, this paper calculated the CDD and HDD using DegreeDays.net. The Integration Method accounts appropriately for temperature fluctuations within each day and between days (BizEE Software 2022). The used software provided a great explanation of degree days calculating and the integration method (BizEE Software 2022).

BizEE Software Limited is a company based in the United Kingdom that develops software to assist businesses and other organisations save energy. In 2008, the company created DegreeDays.net to help energy-saving professionals better use degree days (BizEE Software 2022). According to the developer company, Degree Days.net is an online application that calculates degree days using temperature data from many weather stations worldwide (BizEE Software 2022). BizEE Software is one of the well-developed programs used in various academic publications. For instance, two researchers at Michigan Technological University in the USA did a recent study using the BizEE Software (Warty and Mehendale 2021). Indeed, Degree Days.net was utilised in this research to determine CDD and HDD for the targeted cities in Saudi Arabia.

Table 3.3 and Table 3.4 illustrate the average degree days of cooling and heating (CDD & HDD) from 2017 to 2021, which included varying base temperatures. In particular, different base temperatures for CDD and HDD were tested in this study ranging between 12.5 °C and 24 °C.

3.3.4 Cooling Degree Days

Cooling Degree Day (CDD) is used to understand the cooling demand and energy consumption patterns in a specific location. It is commonly used by architects, engineers, and energy efficiency experts. CDD is a valuable tool for understanding energy consumption patterns and making energy-efficient decisions, especially in hot and arid countries with high air conditioning usage.

*Table 3.3. Five Years Average (2017 to 2021) Cooling Degree Days with varying base temperatures**

No.	Name	CDD 18	CDD 20	CDD 22	CDD 24
1	Jizan	4774.4	4044.1	3315.1	2594.4
2	Madinah	4376.6	3733.8	3133.3	2583.3
3	Jeddah	4252.8	3529.8	2825.9	2160.4
4	Sharurah	4157.7	3515.7	2912.6	2354.5
5	Wadi Al Dawasser	4039.1	3422.6	2848.9	2322.5
6	Yanbu	4012.9	3348	2724	2148.3
7	Dammam	3827	3243.1	2707.6	2221.5
8	Riyadh	3676.2	3116.6	2601.8	2131.2
9	Gassim	3545.4	3006.4	2511.5	2061
10	Najran	3267.8	2671.7	2123.3	1629
11	Bisha	3145.4	2554.8	2015.7	1535.9
12	Al Wejh	3115.6	2459.7	1855.1	1316.5
13	Sakaka	2951.8	2475.3	2038.1	1637.5
14	Arar	2914.9	2458.5	2038.1	1651.9
15	Hail	2867	2382.9	1942.3	1544.2
16	Tabuk	2716.5	2231.7	1791	1395.4
17	Al Taif	2479.2	1926.8	1438.6	1018
18	Al Baha	2327.5	1779.8	1298	888.9
19	Guriat	2052.2	1640.7	1280.3	975.2
20	Khamis Mushait	1465.5	1013.7	659.1	402.6
21	Abha	1220.7	814.4	509.3	298.2

* Base temperatures in Celsius based (°C)

There are several methods for calculating CDD, but the values shown in Table 3.3 are computed using DegreeDays.net based on the integration method. The integrated approach provides a more accurate calculation of CDD using a detailed temperature data record. The CDDs demonstrated in Table 3.3 are listed from highest to lowest for better visual comparisons. The base temperature for CDD calculation is set differently depending on the country, and it is considered a balance between energy consumption for heating and cooling. In this study, a 20°C base temperature has been used. Figure 3.8 shows that Jizan, Madinah, and Jeddah are the hottest cities in the country, with CDD values of 4775, 4377, and 4253, respectively. Meanwhile, Abha requires less cooling, with a CDD value of only 1221, while Khamis Mushait has 1466 CDD. To conclude, the higher the CDD value, the greater the cooling demand and energy consumption.

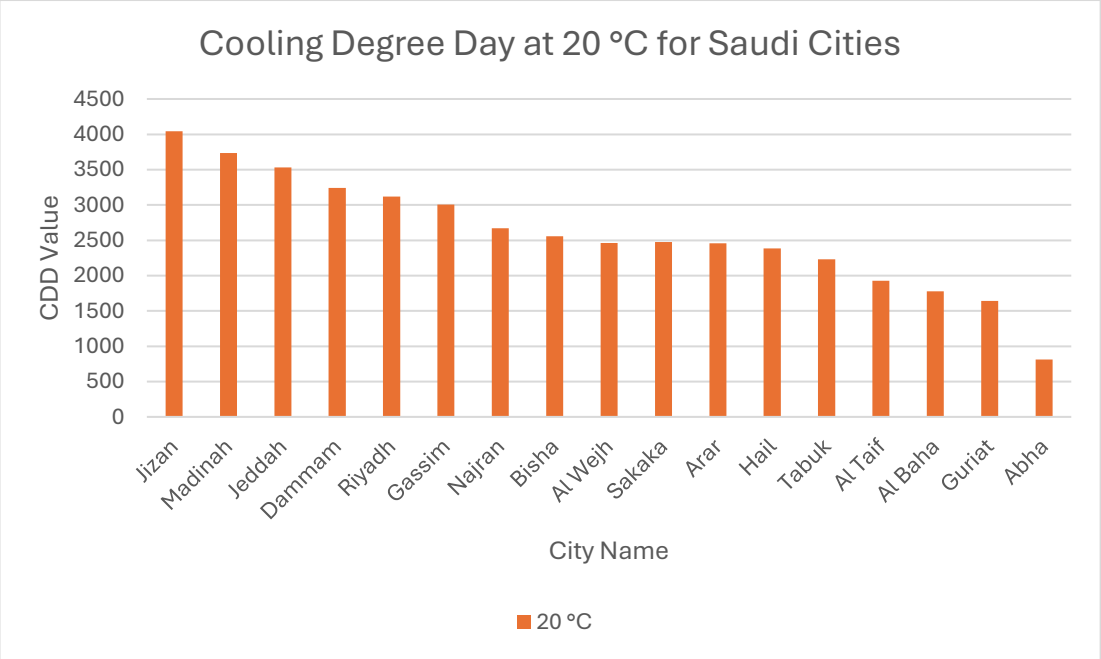


Figure 3.8. CDD for Saudi Cities with a base temperature of 20 °C

3.3.5 Heating Degree Days

Using local weather data, Table 3.4 demonstrates the Heating Degree Days (HDD) value for Saudi Arabia from 2017 to 2021. HDD generated by the DegreeDays.net software and the analysis focusing on the base temperature of 15.5°C. Table 3.4 shows that most cities do not require significant heating. Indeed, the north side of Saudi Arabia is the coldest spot.

*Table 3.4. Five-Year Average (2017–2021) Heating Degree Days with varying base temperatures**

NO	Location Name	HDD 12.5	HDD 13.5	HDD 14.5	HDD 15.5	HDD 16.5	HDD 17.5	HDD 18.5
1	Guriat	341.9	428.7	526.8	637.9	761.2	896.3	1043.5
2	Arar	249.8	320.2	401.3	493.4	597	711.7	838.1
3	Sakaka	194.6	254	324.5	405.7	498.9	603.7	719.2
4	Hail	201.6	259.1	325.9	403.8	493.6	595.2	707.8
5	Tabuk	187.8	244.9	312.2	390.1	478.9	578.7	689.7
6	Abha	65.4	104.1	159.9	234.9	330.1	446.8	585.1
7	Gassim	87.4	121.1	162.9	214.6	275.9	349.1	433.3
8	Riyadh	69.9	97.9	133.3	177	230	293.1	367.6
9	Khamis Mushait	41.8	70	112.2	170.6	248.6	345	463.4
10	Al Taif	34.9	54.1	81.6	119.3	168.1	229.5	304.4
11	Dammam	36.3	56.1	82.4	116.3	158.5	210.7	272.6
12	Bisha	37.7	55.7	79.5	110.7	149.5	198	256.3
13	Al Baha	30.1	46.5	70.4	103.3	148.7	208.4	283.2
14	Najjran	27.5	42.8	64.5	92.7	129.5	175.8	231.6
15	Wadi Al Dawasser	22.8	35.5	53.3	76.7	106.7	145	192.3
16	Sharurah	19.1	28	40.1	56.9	78.6	106.5	142
17	Madinah	6.8	12.7	21.9	35.5	54.9	81.3	116.1
18	Yanbu	2.5	5.6	11.2	19.7	32	50	74.8
19	Al Wejh	0.5	1.6	4.7	11.3	23.3	42.4	69.5
20	Jeddah	0	0	0	0	0.1	0.7	2.3
21	Jizan	0	0	0	0	0	0	0

* Base temperatures in Celsius based (°C)

3.4 Results and Discussion

This research classifies Saudi Arabia's climate based on the cooling degree days due to the need for cooling and then produces a climatic zone map. Figure 3.9 shows the Saudi regions reflecting the CDD values at 20 °C, using the Excel software mapping tools. It helps to define the general boundaries of each zone.

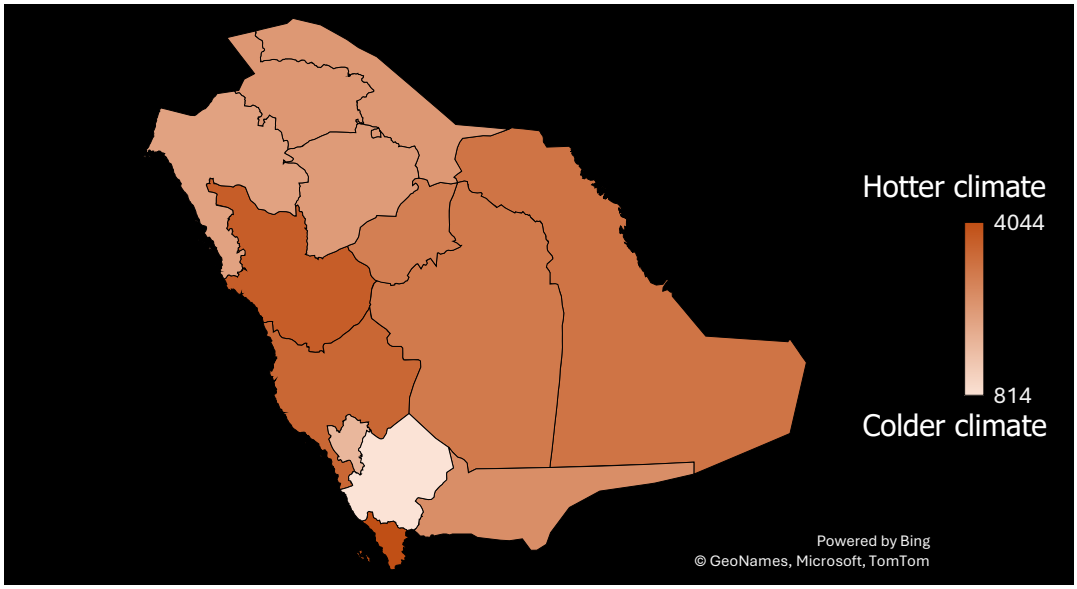


Figure 3.9. Saudi Regions Average CDD Values for Five Years at 20 °C (2017-2021)

The methodology consisted of four components: (1) using local climate data from weather stations for the Saudi cities shown in Table 3.2, (2) calculating CDD and HDD using the integration method with various base temperatures included in Table 3.3 and Table 3.4, (3) categorising SA climates using the calculated CDD of the base temperature of 20 °C into five groups as shown in Table 3.5, and finally (4) generating the Saudi classification climate map, as illustrated in Figure 3.10, with modified boundaries regarding the temperature and humidity. Alula, for instance, matches zone 4 while officially under Madinah governance.

Table 3.5 demonstrates the recommended climatic zones of Saudi Arabia, which classification has five zones. At 20 °C, the maximum CDD value of 4044 was recorded in Jizan, while the lowest 814 was recorded in Abha.

Table 3.5. Categorising of Average CDD Values from 2017 to 2021

Zone No.	City Name	CDD	CDD Classified
1	Jizan	4044	3251 - 4500
	Madinah	3734	
	Jeddah	3530	
	Sharurah	3516	
	Wadi Al-Dawasser	3423	
	Yanbu	3348	
2	Dammam	3243	3151 - 3250
	Al Qaysumah	3200	
3	Riyadh	3117	2501 - 3150
	Gassim	3006	
	Najran	2672	
	Bisha	2555	
4	Sakaka	2475	2001 - 2500
	Al Wejh	2460	
	Arar	2459	
	Hail	2383	
	Tabuk	2232	
5	Al Taif	1927	10 - 2000
	Al Baha	1780	
	Guriat	1641	
	Turaif	1602	
	Khamis Mushait	1014	
	Abha	814	

* Base temperature based is 20 °C

To conclude, Figure 3.10 demonstrates the suggested climate zones for Saudi Arabia, which have five different habited zones. Additionally, Al-Rub' Al-Khali (Empty Quarter) is a sandy, uninhabited desert region, which is illustrated in the grey zone. The climate zones of Saudi Arabia are classified as follows: hot-dry climate, hot-humid climate, warm-humid climate, cold-dry climate, and high-altitude climate. The created climate classification is applicable and can be used in building codes and energy efficiency standards. Zone three can be described as a sea cities area, while zone one is primarily a hot desert zone.

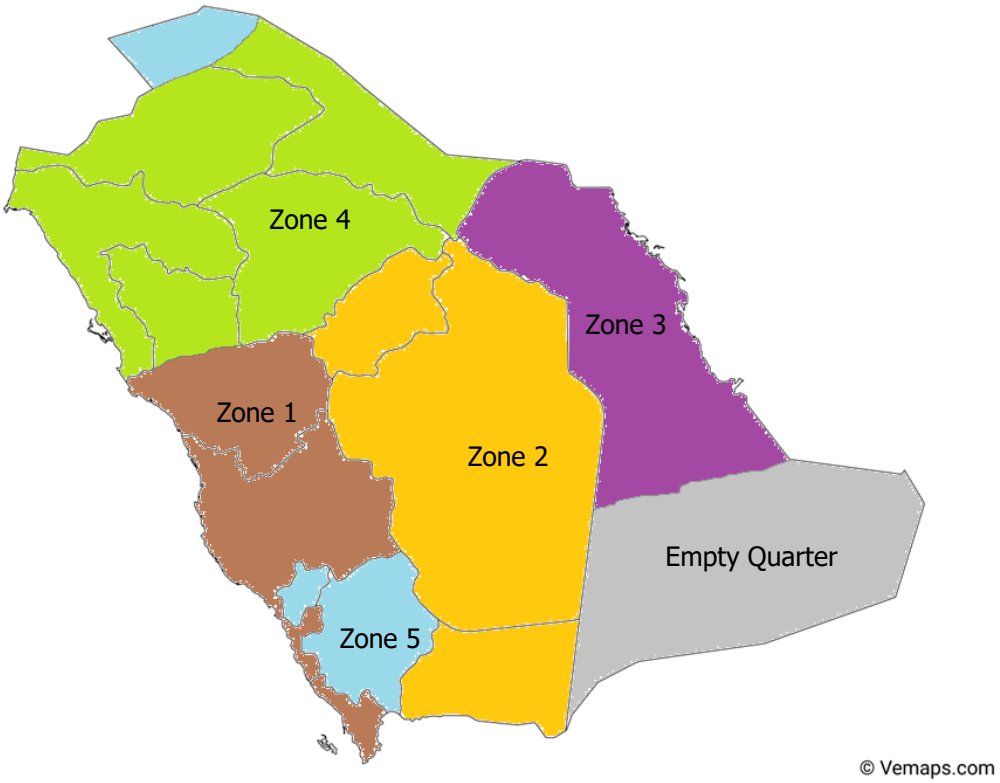


Figure 3.10. Saudi Arabia Recommended Climatic Zoning base map: vemaps.com

3.5 Five Cities Representative Zoning Analysis

3.5.1 Overview

Climate data is available from several reliable worldwide meteorological stations, including the Saudi National Center of Meteorology, the Swiss Meteoblue, and the American Weather Spark. They provide detailed weather reports and diagrams for many cities around the world. The selected Saudi cities will be analysed as follows, Madinah (zone one), Riyadh (zone two), Dammam (zone three), Tabuk (zone four), and Abha (zone five).

'Meteoblue was founded as a company in 2006, and the meteoblue forecast was developed initially at the University of Basel, Switzerland' (meteoblue 2023). The meteoblue provides high-quality local weather data for any location on land or sea worldwide. Meteoblue states, 'The climate diagrams are based on 30 years of hourly weather model simulations' (meteoblue 2023). Weather data of the five represented cities, including Riyadh, Madinah, Dammam, Tabuk, and Abha, are analysed using the meteoblue service.



Figure 3.11. Cities Representing the Saudi Climate Zone

Figure 3.11 presents the five cities that illustrate the recommended climatic zones for Saudi Arabia. Riyadh, the capital city, covers the central zone, including Al Riyadh, Al Qassim, and Najran Regions. Madinah in the west represents Makkah and Madinah, and Jazan regions. While the Eastern Province is presented by its capital city, Dammam. Tabuk City will illustrate the country's north side, including Tabuk, Hail, Al Jouf, and The Northern Border. Finally, Abha city covers the surrounding regions, such as Aseer, Al Baha, and both Quraiat and Turaif in the North of SA.

Figure 3.12 presents the cooling degree days (CDD) for the five selected cities over the years 2020, 2021, and 2022. It highlights the variation in CDD both between locations and across years, with Madinah reaching a maximum of 4000 CDDs in 2021, compared with roughly 700 CDDs for Abha in the same year. This indicates that Madinah experiences a substantially higher cooling demand than Abha, and that 2021 recorded the highest CDD values across all cities.

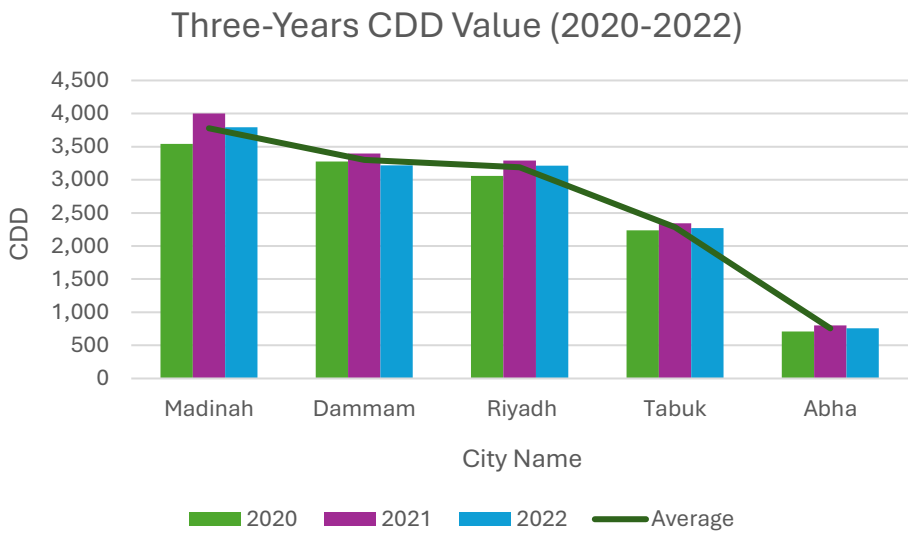


Figure 3.12. Annual CDD of the Selected Cities for 2020,2021 and 2022

The figure also shows that the average CDDs decrease progressively from Madinah to Dammam and then remain relatively stable for Riyadh, before dropping sharply for Tabuk and Abha. This pattern underlines the pronounced climatic gradient among the cities, with considerably lower cooling requirements observed in Abha relative to the other locations.

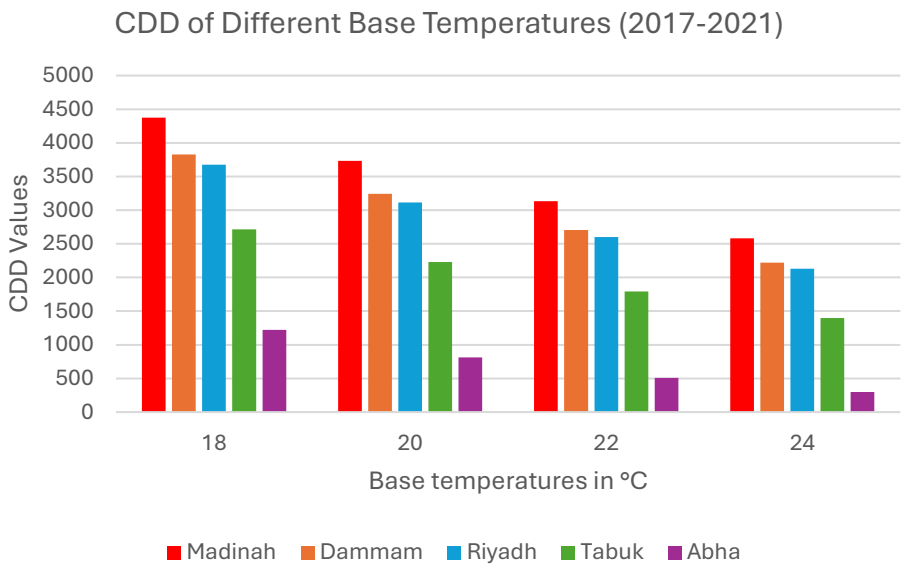


Figure 3.13. CDD for Five Saudi Cities with Various Base Temperatures

Figure 3.13 presents the cooling degree day value for the chosen cities in SA related to their various base temperatures. The lower base temperature increases CDD values, so more cooling is needed. For example, at 20 °C, the graph depicts that Madinah represented the hottest zone which required more cooling, and Abha in the coldest area, which needed less.

Figure 3.14 illustrates the average wind speed for the zoning representative of five cities over the year. It is clearly shown that the wind ranges between 9 kph and 19 kph, which is mostly calm in October that has a low wind speed. Indeed, Dammam received the highest wind speed compared to other cities, with the highest recorded at 18.6 kph in June. In contrast, Abha has the lowest numbers; August has only 9.2 kph.

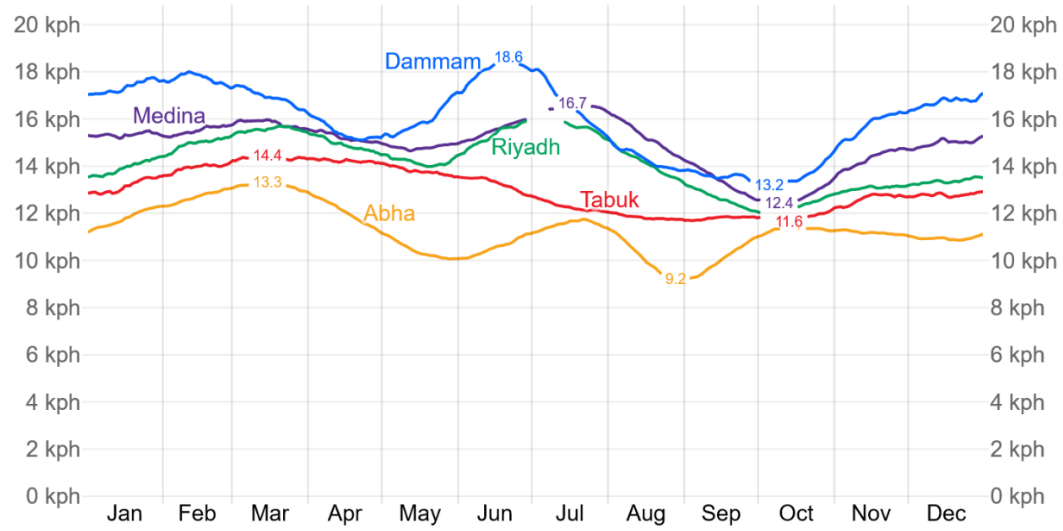


Figure 3.14. Average Wind Speed for Five Saudi Cities *© WeatherSpark.com*

3.5.2 Climate Zone Number One (Hot-Dry and Humid climates)

Several Saudi cities, such as Medina, Yanbu, Makkah, Jeddah, and Jazan, fall under the hot desert or arid climate zone according to the Köppen-Geiger climate classification system. Depending on the specific location and climatic conditions, they are classified under the hot-dry or hot-humid climate zones in the Passive House Planning Package (PHPP). However, the Passivhaus standard is primarily designed for European climates and would require customisation to fully apply to the climatic conditions in the Kingdom of Saudi Arabia.

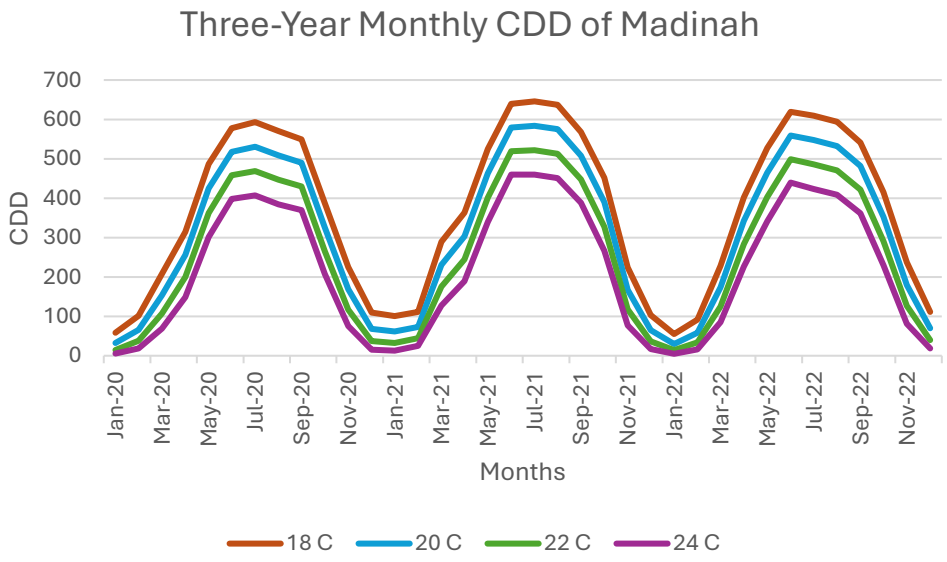


Figure 3.15 Monthly CDD of Madinah for 2020, 2021, and 2022

Madinah is the chosen city representing zone one, located west of Saudi Arabia. The summer in Medina is long, hot, and arid; in contrast, the winter is usually short, cold, dry, and windy. Figure 3.15 depicts Madinah's average monthly cooling degree day over three years, starting in 2020. Furthermore, the chart illustrates that the peak cooling demand occurs in July, while cooling demand reaches its lowest point in January, with negligible heating demand throughout the year. Also, Figure 3.15 shows the effect of a 2 °C gap on the base temperatures. The graph depicts that May through September is the most common time when air conditioning is required to cool the interior environment, contrary to November to March.

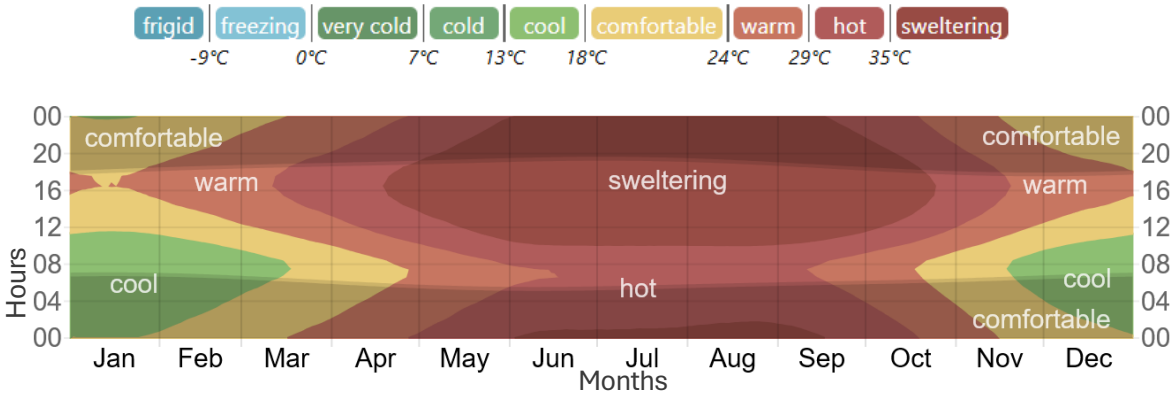


Figure 3.16. Comfort Zone Chart for Medina *© WeatherSpark.com*

Figure 3.16 analysis the monthly average temperature to classify the comfort zone in Madinah, which consists of five categories. The legend colour-coded bars represent the average hourly temperature, and the overlays with shading represent night and civil twilight. Indeed, Madinah's weather is mostly hot over the year.

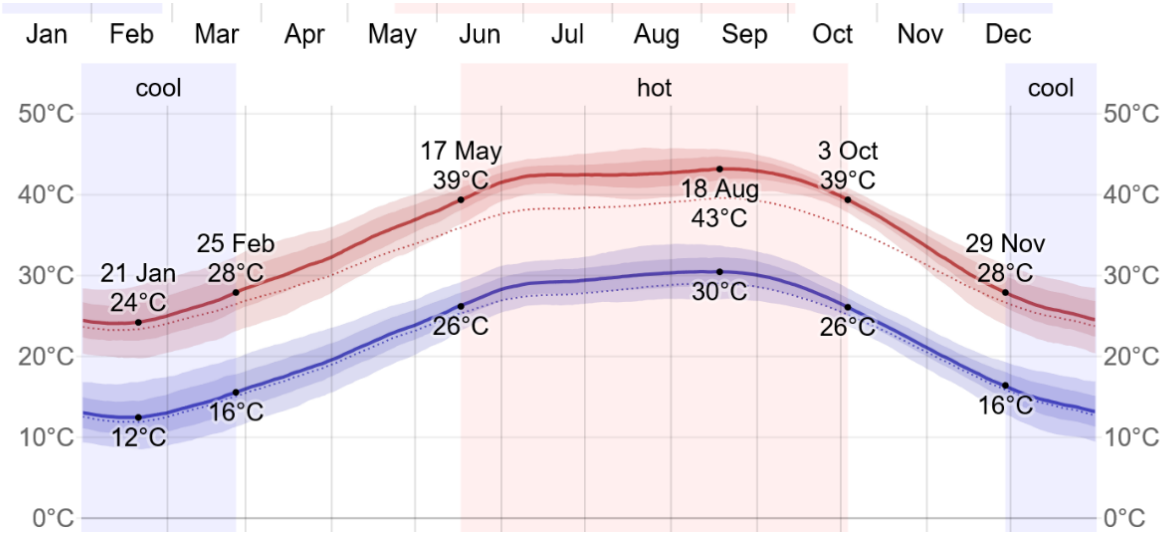


Figure 3.17. Average Seasonal Temperatures in Medina *© WeatherSpark.com*

As shown in Figure 3.17, the average annual temperature in Medina ranges from 12 °C to 43 °C, rarely falling below 9 °C or rising over 46 °C. Figure 3.17 demonstrates the average monthly temperatures, the highest in August and the lowest in January. The low summer season temperature goes between 26 °C and 30 °C in mid-May and early-October. On the other hand, the winter's temperature dropped to 12 °C in January. Figure 3.18 demonstrates the average monthly relative humidity over the year in Madinah, in which the humidity ranges between 13% in June to 37% in December and January. According to (weather&climate 2023), 24% is the annual average relative humidity for Madinah. Throughout the winter, 30 per cent of humidity is observed on average.

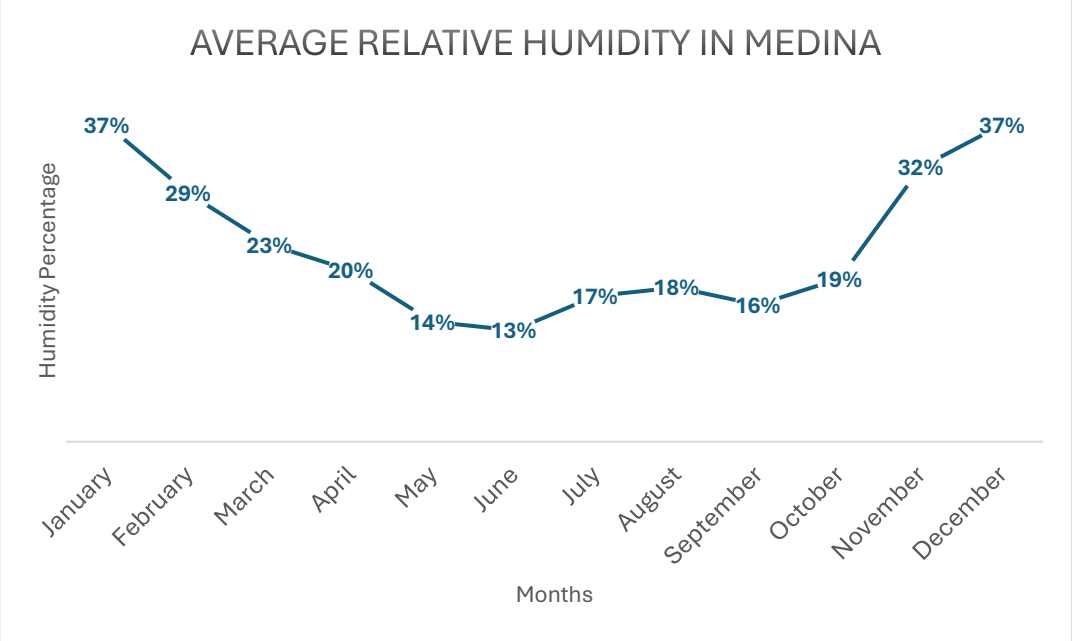


Figure 3.18. Average Relative Humidity in Madinah *data source: climate-data.org*

Figure 3.19 depicts Madinah's annual historical meteorological data, including precipitation, temperature, and wind speed. Specifically, it represents the hot days and cold evenings. Madinah generally receives little rainfall throughout the year, but March, April, and May have the rainiest days.

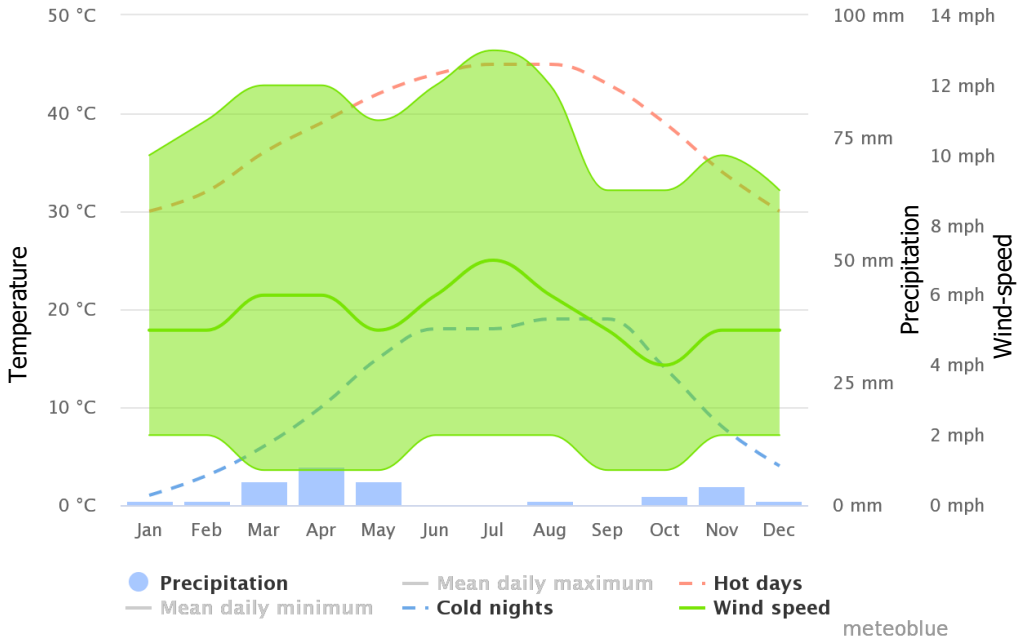


Figure 3.19. Historical Weather Data for Medina (meteoblue 2023)

Figure 3.20 shows the average wind speed in Madinah, with the mean of low and high wind, reported between 10 and 20 kilometres per hour (kph). The city's climate is windy for the majority of the year. July is the windiest month, with a maximum wind speed of 16.7 kph, while October is the calmest month, with a minimum wind speed of 12.4 kph.

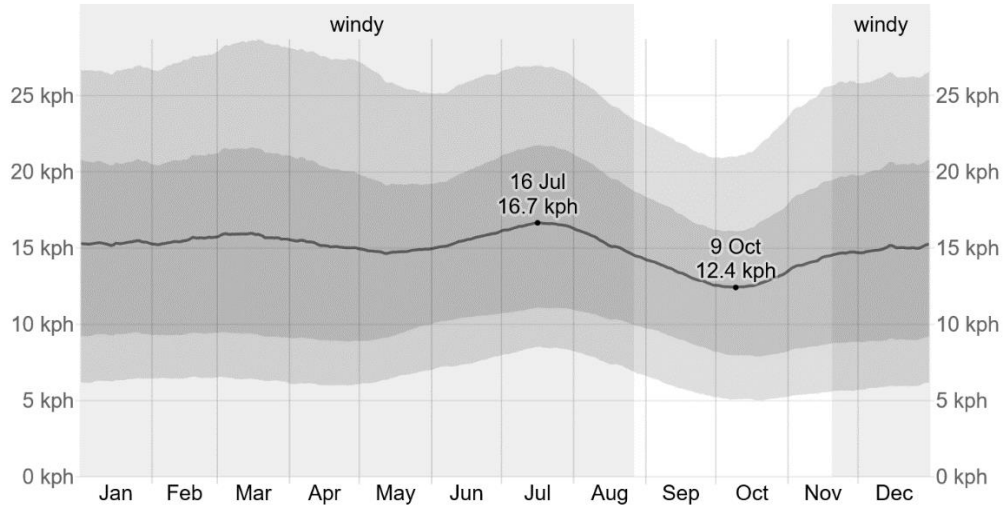


Figure 3.20. Average Monthly Wind Speed in Medina © WeatherSpark.com

3.5.3 Climate Zone Number Two (Hot desert or arid climate)

Zone two includes various Saudi cities, including Riyadh, Buraidah, Bisha, and Najran. Riyadh is representative of the zone. Figure 3.21 analyses the monthly average temperature to categorise Riyadh's comfort zone, which consists of five categories cool, comfortable, warm, hot, and sweltering. The legend's colour-coded bars depict the average hourly temperature, while the overlays with shade indicate night and civil twilight.

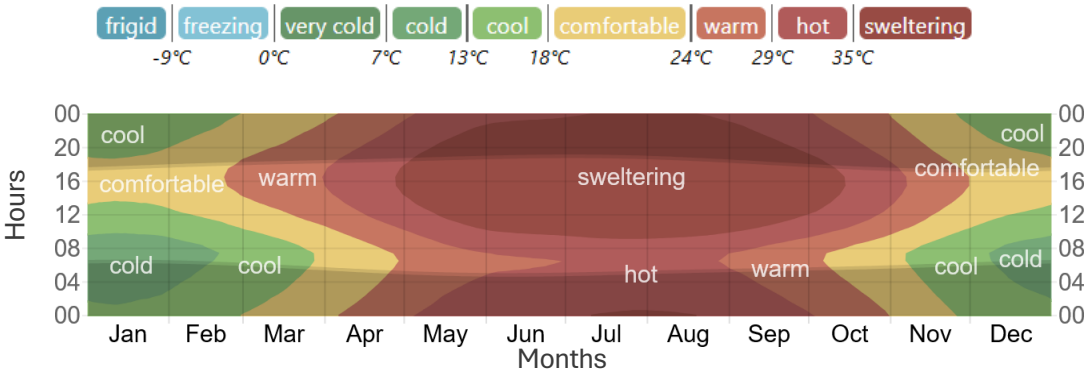


Figure 3.21. Average Hourly Temperature in Riyadh © WeatherSpark.com

As seen in Figure 3.22, Riyadh's annual average temperature ranges from 9 °C to 43 °C, rarely dipping below 8 °C or rising over 43 °C. July has the highest recorded temperature over the year, while January has the lowest average monthly temperature. In mid-May and late September, the summer lows often remain between 26 and 30 degrees Celsius. Temperatures fell below 9 degrees Celsius in January.

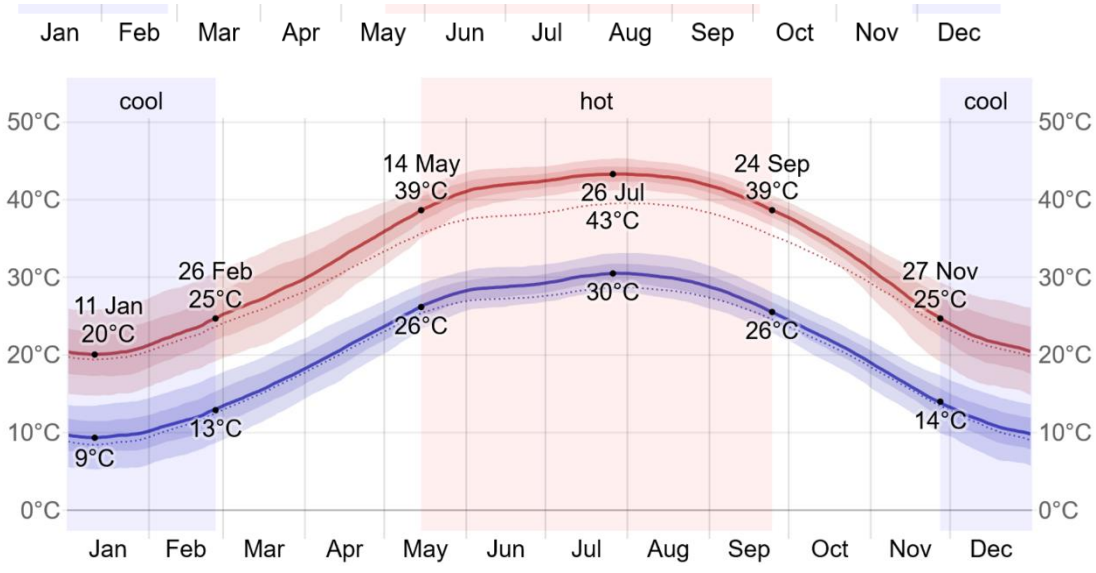


Figure 3.22. Average Seasonal Temperatures in Riyadh © WeatherSpark.com

Figure 3.23 depicts the average relative humidity for each month of the year in Riyadh, which ranges from 10 per cent in June to 44 per cent in December and January. The percentage increased rapidly from 18 per cent to 35 per cent between October and November. The average annual humidity for the city is 23 per cent.

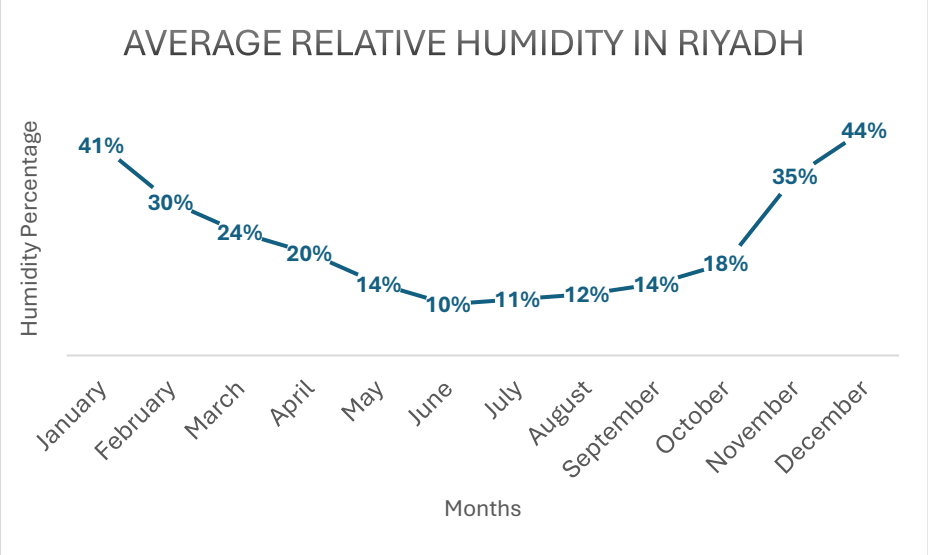


Figure 3.23. Average Relative Humidity in Riyadh data source: climate-data.org

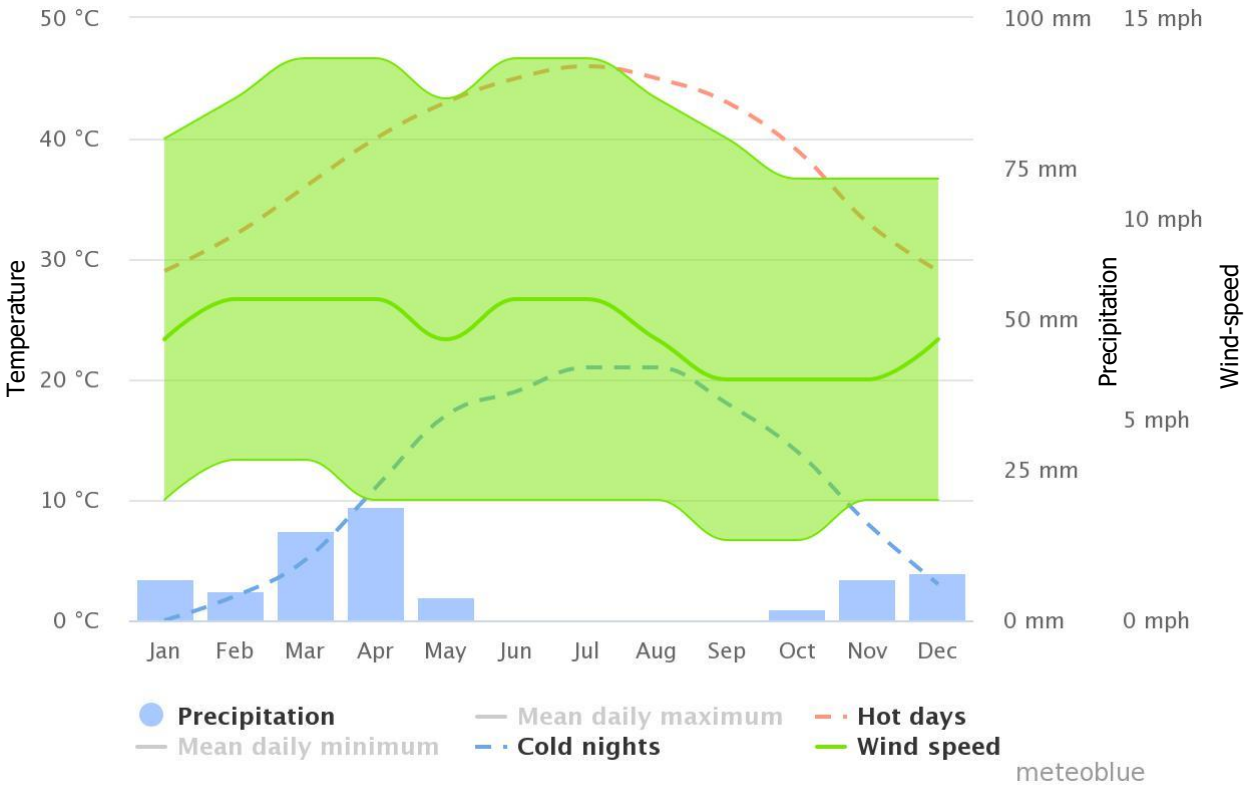


Figure 3.24. Historical Weather Data for Riyadh (meteoblue, 2023)

Figure 3.24 illustrates Riyadh's annual historical weather data, including precipitation, wind speed, and temperature. It reflects explicitly the warm days and cool nights. Riyadh receives the rainiest days throughout the year between October and May. April gets the most rain, with almost 25 mm. In contrast, minimal precipitation between June and September.

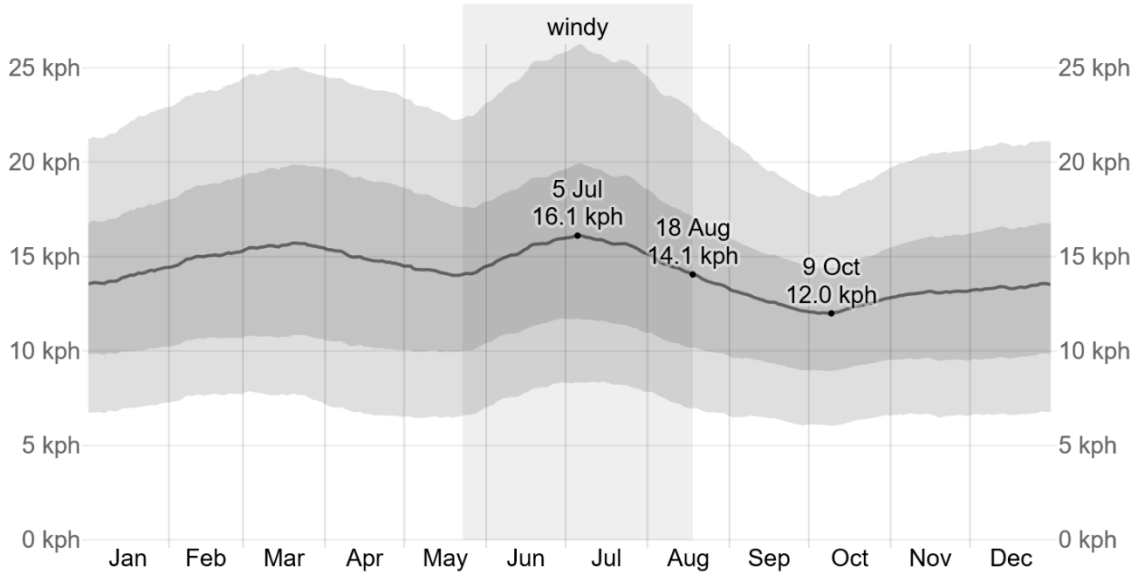


Figure 3.25. Average Monthly Wind Speed in Riyadh © WeatherSpark.com

The average wind speed in Riyadh is depicted in Figure 3.25, with the mean of low and high wind believed to be between 9 and 20 kilometres per hour. The city's climate is moderate wind most of the year. The windiest month is July, with a maximum wind speed of 16.1 kph, while the calmest month is October, with a minimum wind speed of 12 kph. The windy season goes from Late May to late August. The highest wind recorded over the year is over 25 kph in July.

3.5.4 Climate Zone Number Three (Hot Humid semi-arid climates)

The third zone contains several Saudi cities, including Dammam, Dhahran, and Aljubail. Specifically, Dammam represents the zone. Figure 3.26 analyses the monthly average temperature to classify Dammam's comfort zone, which consists of five categories: cool, comfortable, warm, hot, and oppressive. The colour-coded bars in the caption represent the average hourly temperature, while the overlays denote night and civil twilight.

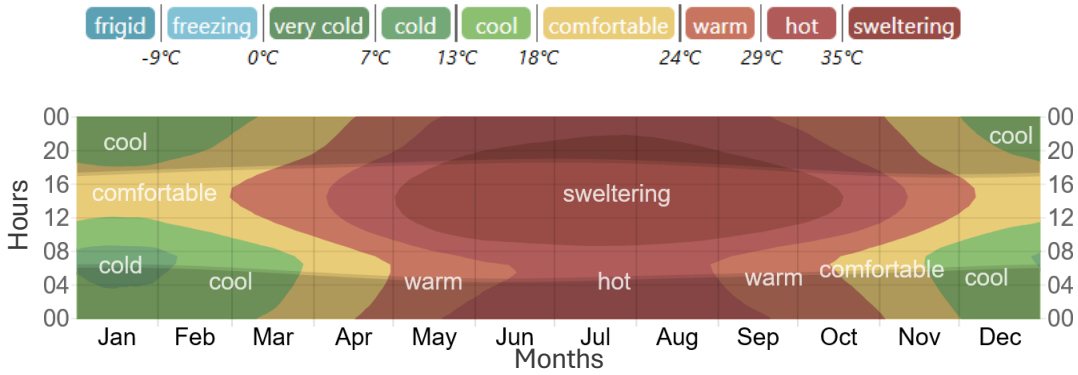


Figure 3.26. Average Hourly Temperature in Dammam © WeatherSpark.com

As shown in Figure 3.27, Dammam's annual average temperature ranges between 11 °C and 43 °C, rarely falling below 10 °C or exceeding 45 °C. July has the highest average yearly temperature, while January has the lowest monthly average temperature. The minimal summertime temperature ranges from 25 to 30 degrees Celsius between mid-May and late September. The temperatures fell below nine degrees Celsius in December and January.

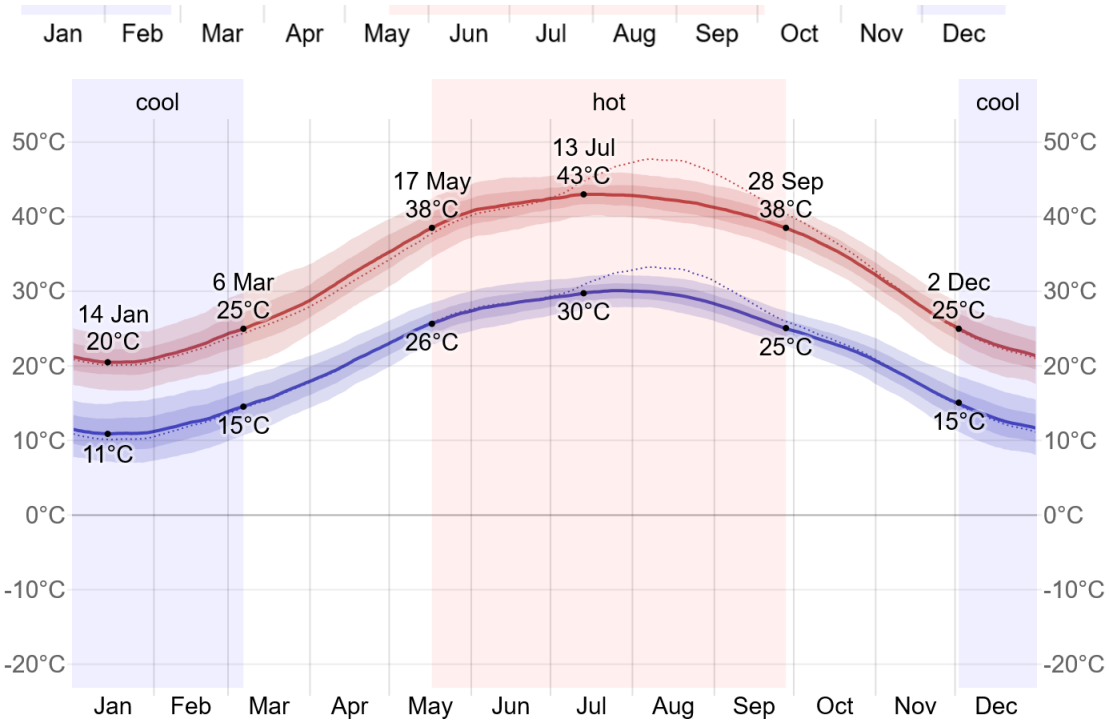


Figure 3.27. Average Seasonal Temperatures in Dammam ©WeatherSpark.com

Figure 3.28 displays the monthly average relative humidity in Dammam, which ranges between 38 % in June and 66 % in December and January. The humidity percentage decreased continuously from its summit at 66% in January to 38% in June. The average annual humidity for the city is 54 per cent.

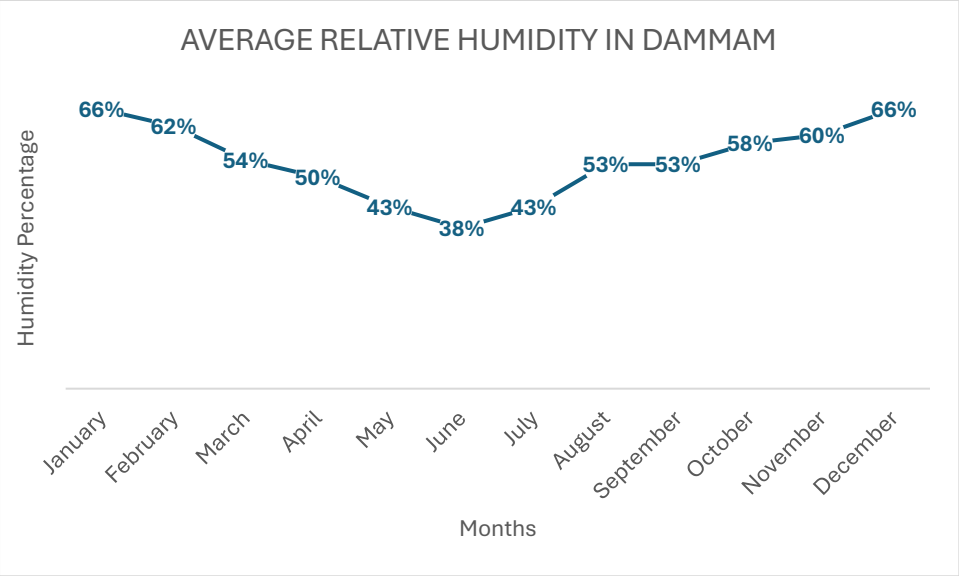


Figure 3.28. Average Relative Humidity in Dammam data source: climate-data.org

Figure 3.29 depicts annual meteorological data for Dammam, including wind speed, temperature, and precipitation. It reflects the warm days and cool evenings. Dammam receives the most rainfall throughout the year between November and April. March is the rainiest month, with nearly 15 mm. While between June and September, minimal precipitation is specified in contrast. In addition, Figure 3.30 depicts the average wind speed in Dammam, with the mean of low and high wind speeds estimated to be between 13.2 and 18.6 kilometres per hour. The windiest month is June, with a maximum wind speed passing 30 kilometres per hour, while September and October are the calmest, with a top wind speed of 14 kilometres per hour. The breezy season lasts from the end of May to almost the end of July.

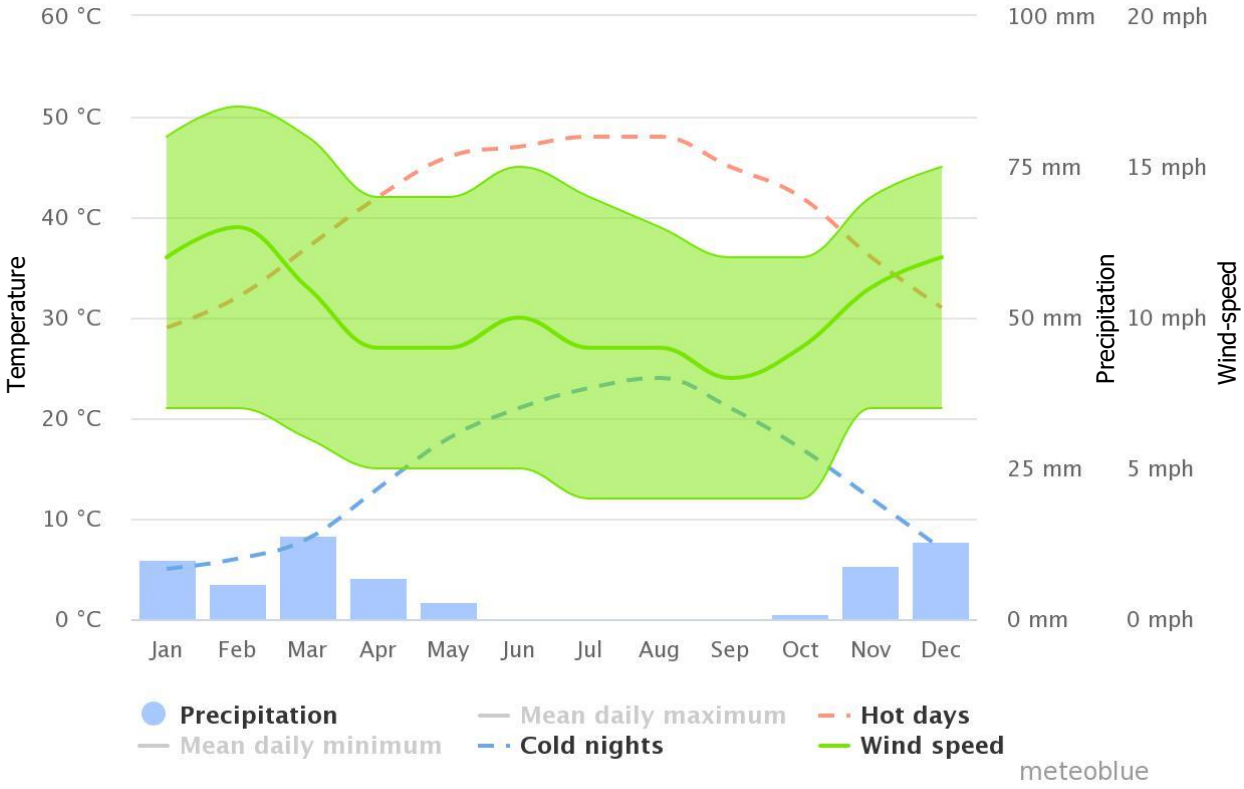


Figure 3.29. Historical Weather Data for Dammam (meteoblue, 2023)

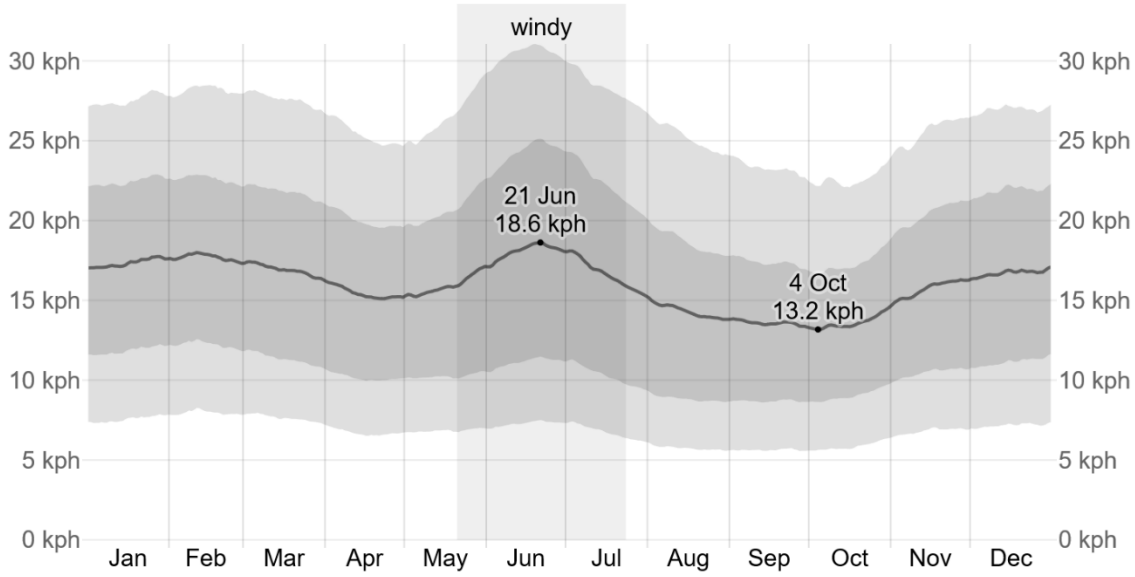


Figure 3.30. Average Monthly Wind Speed in Dammam © WeatherSpark.com

3.5.5 Climate Zone Number Four (Warm and Cold desert climates)

Zone four encompasses various Saudi cities, including Hail, Tabuk, and Al Wajeh. Tabuk serves as the representative city for this zone. Figure 3.31 analyses the monthly average temperature in Tabuk to classify its comfort zone, which consists of five categories: relaxed, comfortable, warm, hot, and sweltering. The legend uses colour-coded bars to represent the average hourly temperature, while the shaded overlays indicate the night and civil twilight periods.

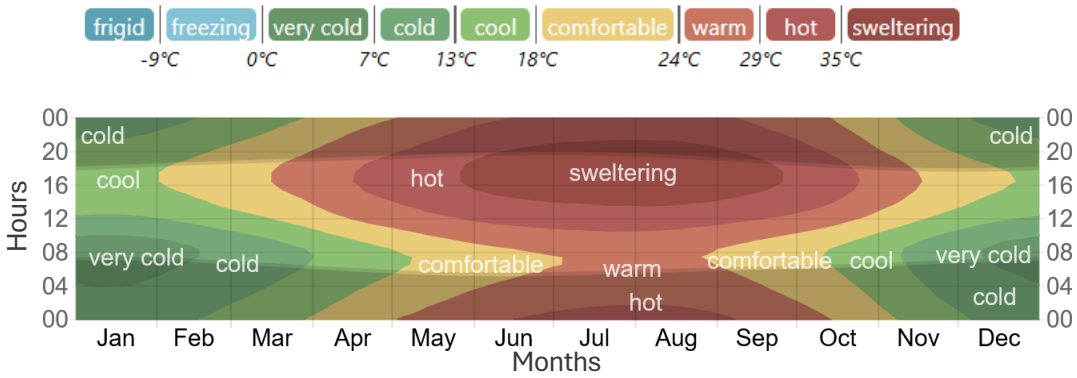


Figure 3.31 Average Hourly Temperature in Tabuk © WeatherSpark.com

Figure 3.32 depicts the annual average temperature in Tabuk ranges from 5 °C to 39 °C, seldom dropping below 1 °C or exceeding 40 °C. August records

the highest temperatures throughout the year, whereas January and December experience the lowest average monthly temperature. Most of the summer is between June and September, with the minimum summer temperature ranging from 20 to 25 degrees Celsius. In January, cold temperatures can drop below 5 degrees Celsius during winter, and the average temperature starts at 5 and 22 degrees.

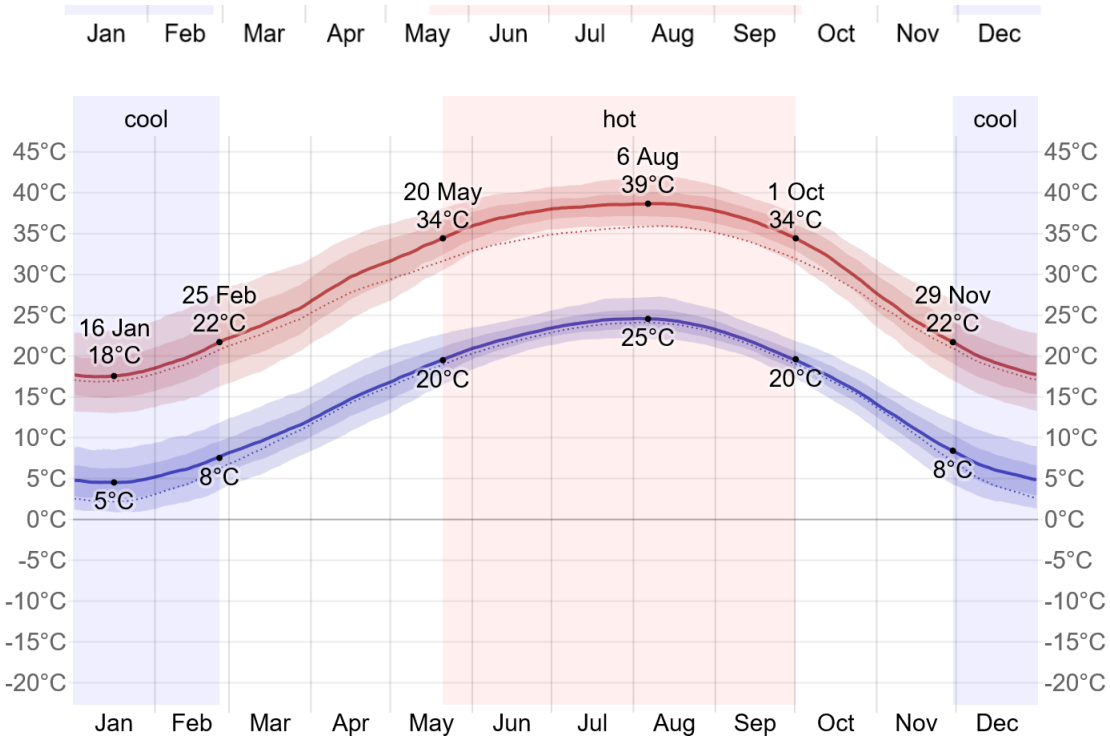


Figure 3.32. Average Seasonal Temperatures in Tabuk ©WeatherSpark.com

Figure 3.33 illustrates the average humidity for each month in Tabuk. The average annual humidity in the city is 28%. The highest percentages are 44%, 43%, 34%, and 38% during the cold season for January, December, November, and February, respectively. The number increased rapidly from 28% in October to 38% in November.

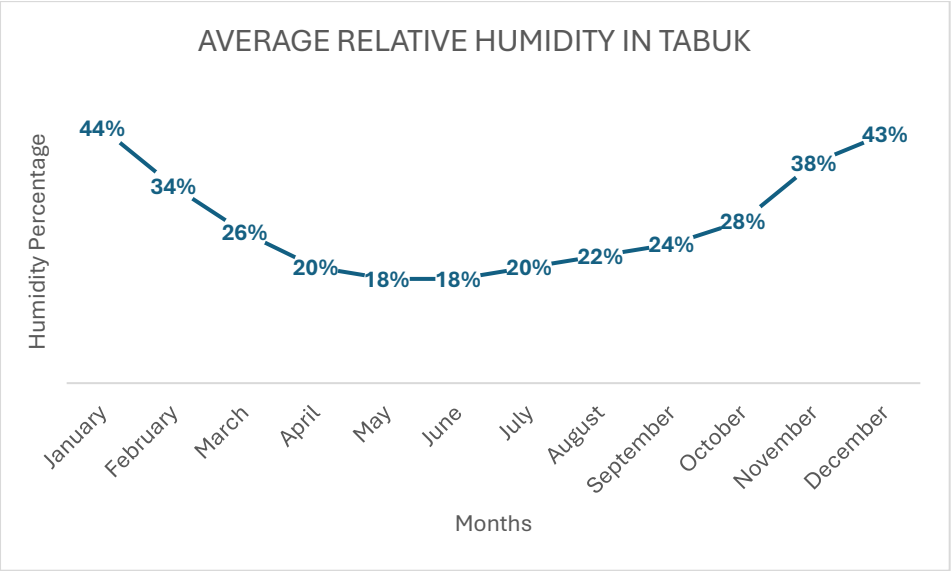


Figure 3.33. Average Relative Humidity in Tabuk data source: climate-data.org

Figure 3.34 presents the annual historical weather data for Tabuk, including precipitation, wind speed, and temperature. It specifically highlights the occurrence of warm days and cool nights. Tabuk experiences the rainiest days between October and May, with March receiving the highest precipitation of nearly 5 mm. In contrast, minimal rainfall occurs between June and September. Moreover, the average wind speed in Tabuk is depicted in Figure 3.35, with the mean of low and high wind speeds ranging between 11.6 and 14.4 kilometres per hour. The city experiences moderate wind conditions for most of the year. Both March and April stand out as the windiest months, with a maximum wind speed of about 14 kph, while October is the calmest month, with an average minimum wind speed of 12 kph. The windy season typically extends from mid-January to late June, with the highest recorded wind speed exceeding 20 kph.

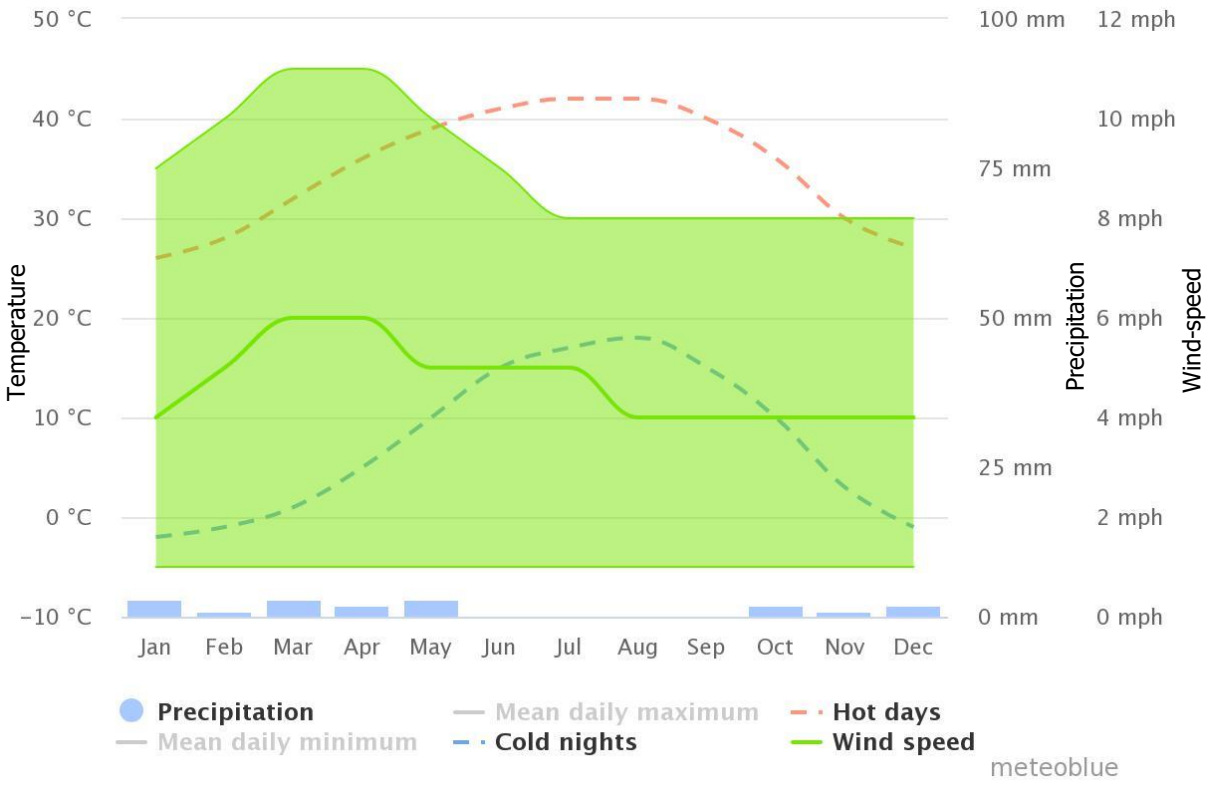


Figure 3.34. Historical Weather Data for Tabuk (meteoblue, 2023)

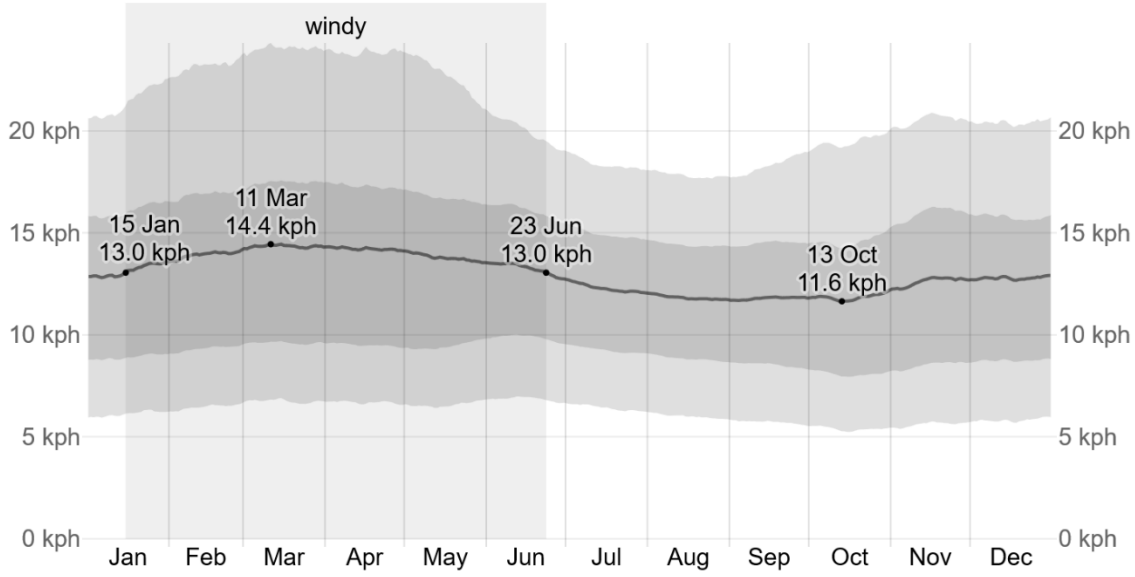


Figure 3.35. Average Monthly Wind Speed in Tabuk © WeatherSpark.com

3.5.6 Climate Zone Number Five (Cold semi-arid climates)

The Comfort Zone Chart for Abha, presented in Figure 3.36, categorises the city's climatic conditions into five categories: chilly, comfortable, warm, hot, and scorching. Figure 3.36 provides a detailed classification for each month of the year, allowing for an in-depth understanding of the varying degrees of comfort encountered in Abha. By colour-coding the various categories and depicting monthly variations, the illustration provides valuable insights into the temperature patterns and aids in determining the year-round thermal comfort in Abha.

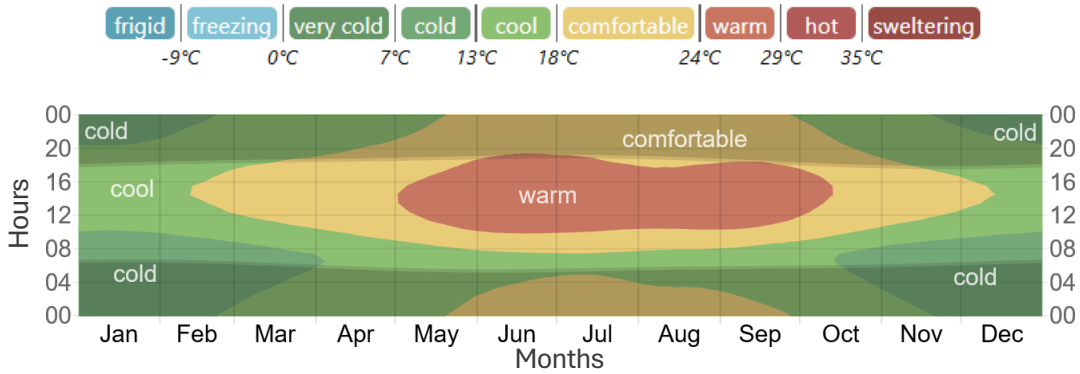


Figure 3.36. Average Hourly Temperature in Abha *© WeatherSpark.com*

Figure 3.37 provides an overview of the maximum and minimum temperatures recorded in Abha monthly throughout the year. It also highlights the months corresponding to the cooling and hot seasons. According to the diagram, June records the highest maximum temperature, reaching 28 degrees Celsius, indicating the onset of the hot season. Conversely, December is the coldest month, with a minimum temperature of only 7 degrees Celsius. During the summer, temperatures range between 15 and 28 degrees Celsius, while in winter, they vary from 7 to 20 degrees Celsius, indicating the cooler conditions of the winter season. This chart offers valuable information on the temperature trends in Abha and helps identify the distinct seasons experienced in zone number five.

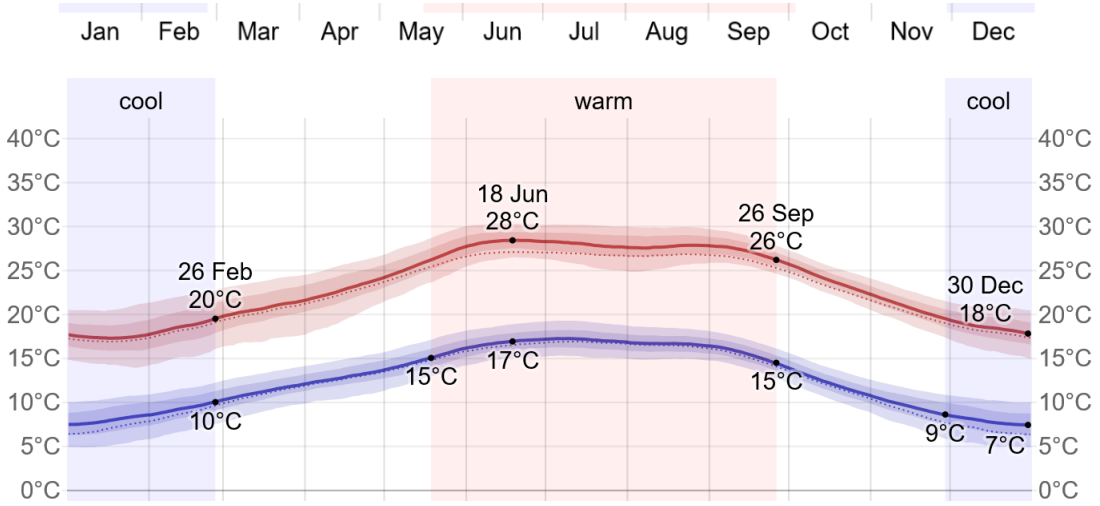


Figure 3.37. Average Seasonal Temperatures in Abha ©WeatherSpark.com

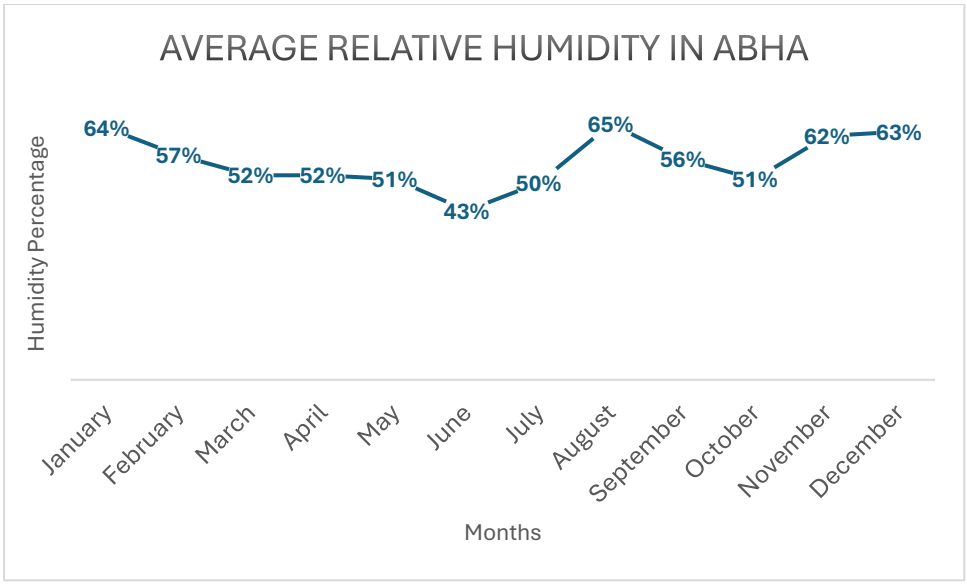


Figure 3.38. Humidity for Abha data source: climate-data.org

Figure 3.38 illustrates the average monthly humidity percentages for Abha City in southern Saudi Arabia throughout the year. The data highlights the city's consistently high relative humidity throughout the year, with the peak recorded in August at 65%. In contrast, June experiences the lowest humidity level at 43%. The findings underscore the significance of understanding humidity patterns in Abha City, aiding in urban planning and environmental management initiatives for enhanced comfort and well-being.

Based on the historical weather data for Abha shown in Figure 3.39, it is evident that the city receives a higher amount of rainfall compared to other cities in the country. Figure 3.39 indicates that July and August are the months with the majority of the rain, with August experiencing the highest peak precipitation, reaching approximately 130 mm. Additionally, the wind speed in Abha ranges between 4 and 7 kilometres per hour (kph), while September and October stand out as the months with the highest level of wind.

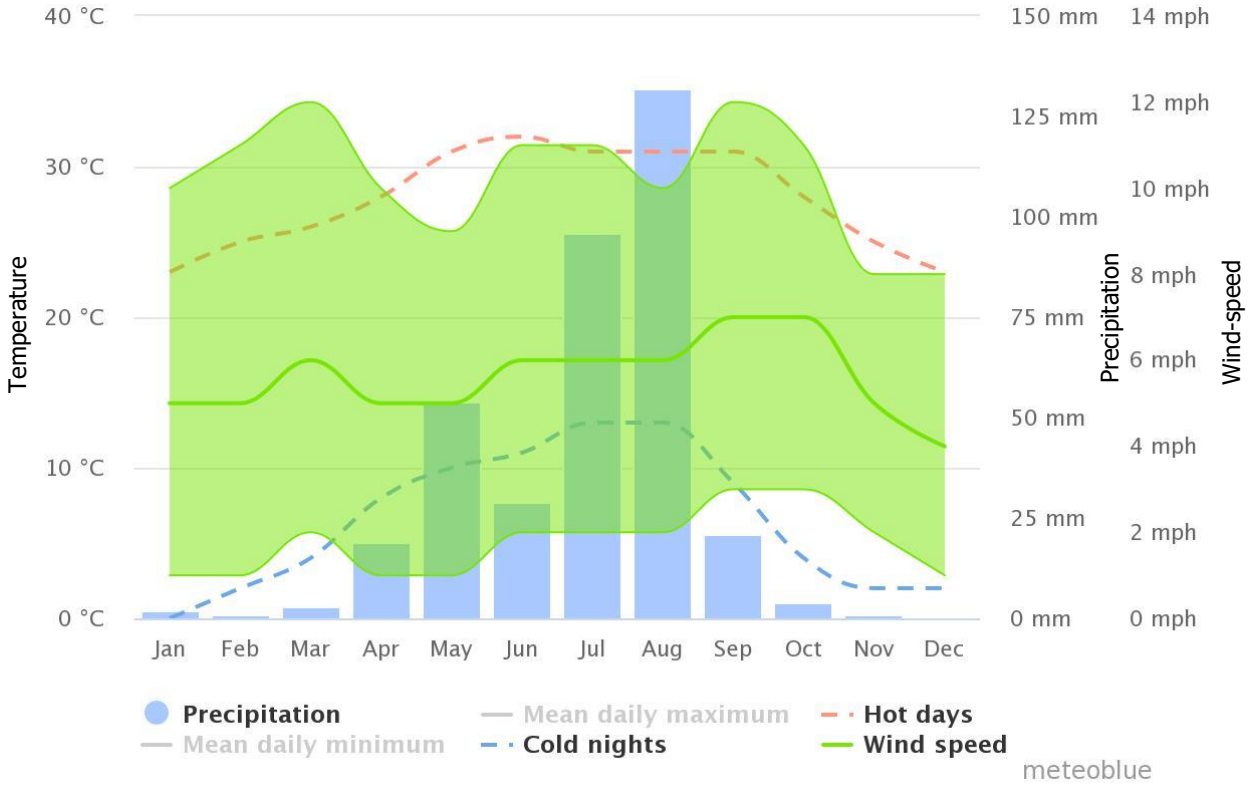


Figure 3.39. Historical Weather Data for Abha (meteoblue, 2023)

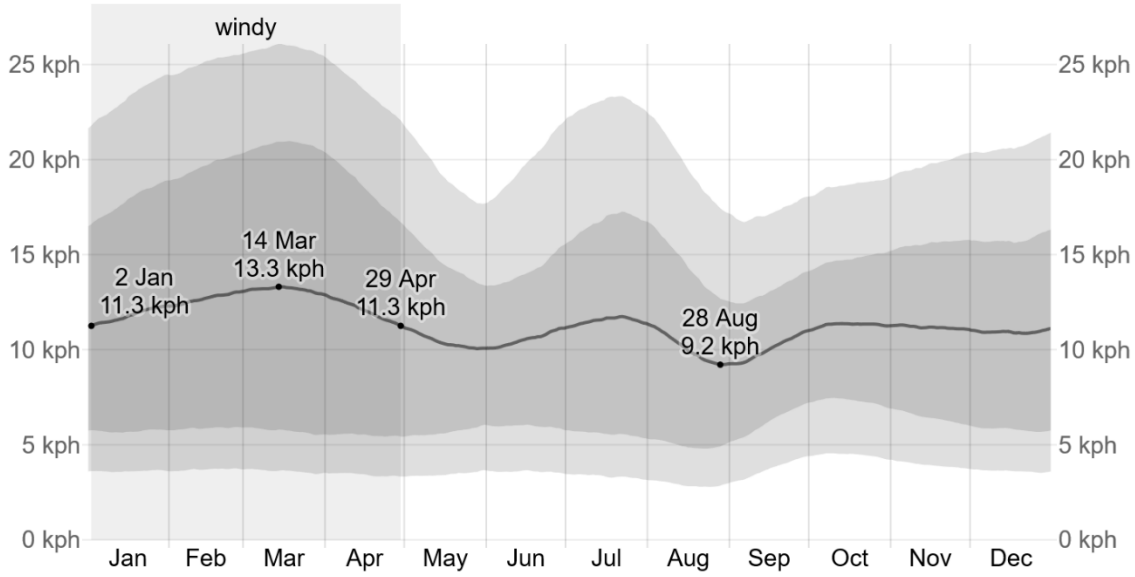


Figure 3.40. Average Monthly Wind Speed in Abha *© WeatherSpark.com*

Figure 3.40 depicts Abha's monthly airflow throughout the year. It is noticeable that the strong winds season runs from January to April, with a peak of 13.3 kilometres per hour in mid-March. August and September have the least wind, with only 9.2 kph recorded in August. On average, the annual wind speed fluctuates between 9 and 14 kilometres per hour.

In conclusion, a refined climatic zoning based on multi-year cooling degree days established Madinah, Riyadh, Dammam, Tabuk and Abha as representative cities of five Saudi climatic zones, each associated with clearly differentiated cooling demand.

4 PASSIVHAUS STANDARD

4.1 Introduction

4.1.1 Overview of the standard

'Passivhaus is the world's leading standard in energy efficient construction' (iPHA 2016). A Passivhaus building uses so little cooling and heating that it provides a pleasant internal atmosphere (Schnieders, Feist et al. 2015). In other words, Passivhaus buildings maximise occupant comfort while consuming minimal energy for cooling and heating (Passivhaus Trust 2021). Thus, passive house standards such as the German Passivhaus standard have been widely adopted internationally. 'Passivhaus (PH) standard first emerged as a construction principle applied to residential buildings' (Khalfan 2017). According to (Khalfan 2017), the Passivhaus term 'in German refers to a passive house or building, and some references might use the English translated version "Passive House".' In 1988, the concept of "Passivhaus" was introduced due to a research project by two professors from Germany and Sweden (Moreno-Rangel 2020). Professor Wolfgang Feist (German) is from the Institute for Housing and Environment, and the second professor is Bo Adamson (Swedish) from Lund University (Moreno-Rangel 2020).

Passivhaus buildings are highly energy-efficient structures that reduce energy consumption by increasing the thermal and airtightness performance of the building envelope (Liu, Sharples et al. 2021). Professor Feist claimed that 'The Passivhaus standard can be used and applied in any country' (Dequaire 2012). Backed by over 30 years of international evidence, the PH standard is a proven solution that provides us with a range of tested methods to deliver new and existing buildings that are net-zero, grid-optimised, and improve the health and well-being of occupants (Passivhaus Trust 2021). According to PHI, there are more than 33,000 certified Passivhaus units globally as of January 2022 (iPHA 2022). This overall project number illustrates that the Passive House has grown fast.

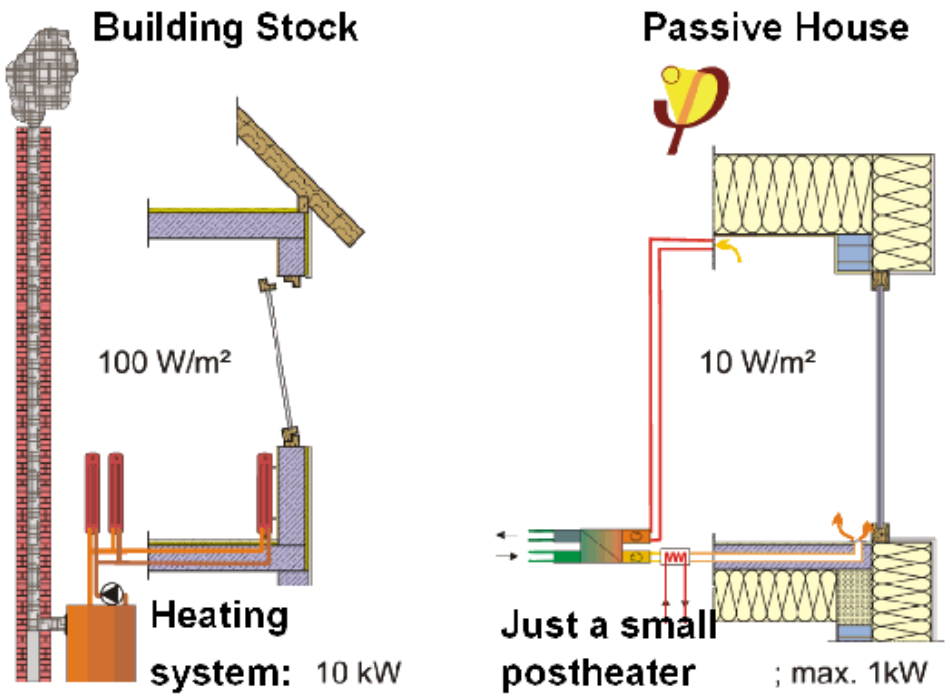


Figure 4.1. Fundamental principles of a Passive House (Feist 2006)

Figure 4.1 illustrates the main landscape principles for the Passivhaus design, including explaining the difference between 'traditional' building construction and a Passivhaus building. The Passivhaus concept explicitly improves the insulation of external components, airtightness, passive solar gain, and heat recovery from an air supply (Feist, Pfluger et al. 2020).

4.1.2 Passivhaus development

The Passive House (Passivhaus) development began with a research project to find the limits of improvement in building energy efficiency (Feist, Pfluger et al. 2020). In five developments, solutions were developed for thermal bridge-free buildings, improved window insulation, airtight structures, efficient air-to-air heat recovery systems and ventilation controls suitable for indoor air quality (Feist, Pfluger et al. 2020). The results of these developments flowed into the first occupied passive demonstration building design (Feist, Pfluger et al. 2020).

In October 1991, the Passive House pilot project was built in Darmstadt, Germany (Feist 2015). It was designed by architects Prof. Bott / Ridder / Westtermeyer (Feist, Pfluger et al. 2020). The project is a three-storey terraced house with four residential units for different clients, including Prof Feist (Feist 2015). It is the first construction Passive House project in the world. The terraced residences are considered a pioneer project for the Passivhaus standard after the householders moved in 1991 with their families (iPHA 2021). Moreover, the project received the Passive House Plus certificate after installing a photovoltaic system in 2015, utilising renewable energy (iPHA 2021). The updated pioneer Passivhaus project is represented in Figure 4.2 as receiving the PH Plus certification.

In 1996, Passive House Institute (PHI) was founded by Prof Wolfgang Feist, with its headquarters in Darmstadt, Germany (Krämer 2020). PHI is an independent research institute for highly efficient energy use in buildings (Krämer 2020). The Institute is internationally leading in research and development in energy efficient construction (iPHA 2021). Many Passivhaus activities go under the umbrella of the PHI, such as holding the annual premium conference, publishing Passivhaus updates, and providing the official certificate.

There is also the International Passive House Association (iPHA), a global Passivhaus platform. The Passive House Institute established the iPHA to advance the Passivhaus standard and the quality it represents worldwide (iPHA 2022). The iPHA "works to promote the Passive House Standard and foster a greater public understanding of highly energy efficient buildings" (iPHA 2022). The iPHA is a 'worldwide network of Passivhaus stakeholders including architects, planners, scientists, suppliers, manufacturers, contractors and property developers' (iPHA 2022).



Figure 4.2. The First Passivhaus project (PHP 2021)

4.1.3 Passivhaus main principles

The Passivhaus approach evolved from Swedish super-insulated houses and passive solar buildings to minimise space heating and improve heat transfer (U-value) to the building envelope (fabric, doors and windows) (Moreno-Rangel 2020). These developments have driven advances in thermal insulation, thermal bridging, airtightness, controlled ventilation, and the commercialisation of triple-glazed windows (Moreno-Rangel 2020).

Figure 4.3 illustrates the five fundamental principles of the Passivhaus standard, including (1) super insulation, (2) high-performance windows, (3) mechanical heat recovery ventilation systems, (4) airtight building envelope, and (5) thermal bridge free construction. Also, the diagram indicates the principles' concept of each aspect of the standard.

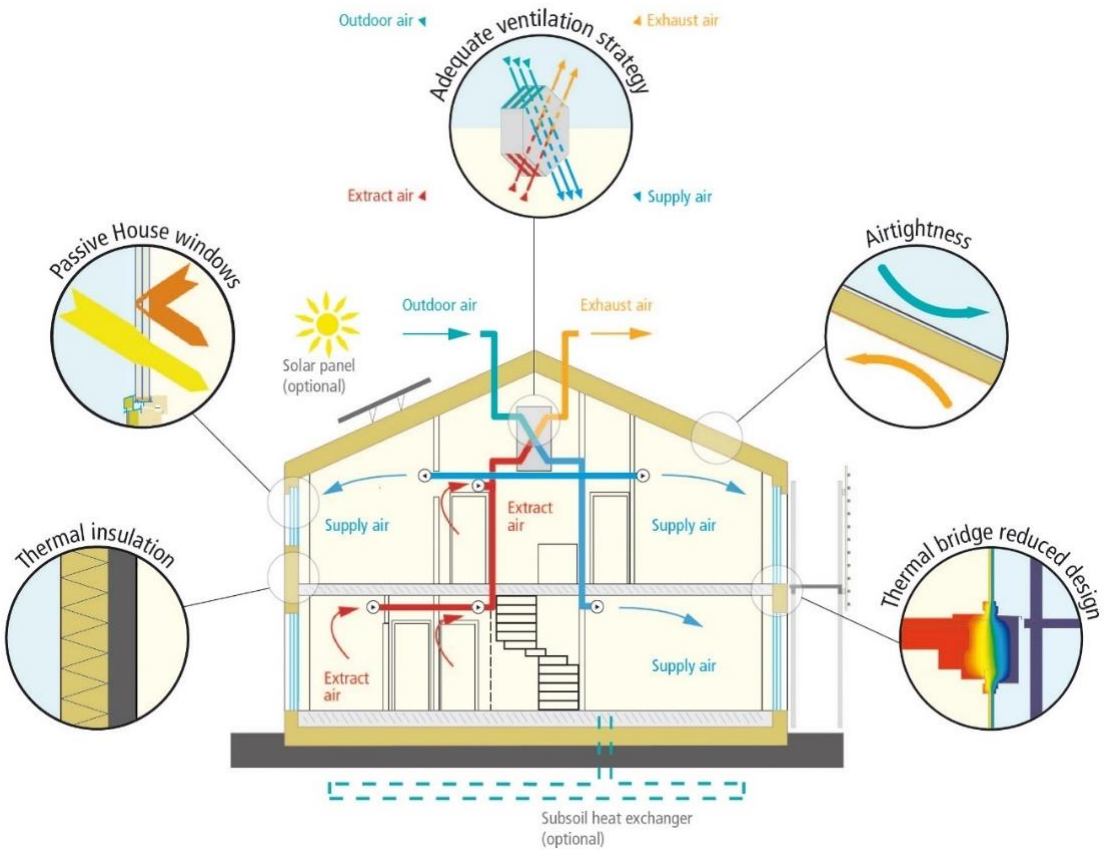


Figure 4.3. Passivhaus standard requirements (PHI 2015)

The Passivhaus standard principles in detail are as follows:

1. Super-insulation

Passivhaus buildings use super insulation on the outside walls, floors, and ceilings to reduce heat transfer (Moreno-Rangel 2020). It has to be high-quality insulation. The average U-values (0.10–0.15 W/m^{2}K) necessary for Passivhaus walls may be reached through a broad spectrum of thermal insulation (Moreno-Rangel 2020). Thus an exterior thickness of a Passivhaus insulation range from 200 and 400 mm, using polystyrene, polyurethane foam, mineral wool, and cellulose (Moreno-Rangel 2020). Indeed, the insulation maintains a high indoor comfort and minimises the needed heating or cooling.

2. Passivhaus windows

It is important to install quality windows that are well insulated and require frame insulation. 'The average temperature of internal window surfaces should not fall below 17°C on a cold day' (PHI 2018). Passivhaus windows include frames intended to maximise solar benefits, which warm up the structure (Moreno-Rangel 2020) in a cold climate. While in hot climates, solar control glass may successfully minimise solar thermal loads when heating is not required. Most Passivhaus windows have two or three layers of glass filled with an inert gas like argon. 'The glass allows visible light to enter the building while blocking heat by filtering infrared and ultraviolet waves, which is known as "spectral selectivity". Thus Passivhaus buildings in hot climates should generally have windows with a selectivity of 2 or higher (PHI 2018). The Passivhaus windows ensure a comfortable indoor environment and minimum energy usage.

3. Thermal bridge free construction

A thermal bridge is a building envelope component that transmits heating or cooling between the inside and outside. Plan and execute all edges, corners, connections, and penetrations to avoid thermal bridges (PHI 2021). Also, when thermal bridges cannot be prevented must be minimised to the greatest extent practicable. Thermal bridges in Passivhaus buildings might generate condensation and constitute a source of unquantified thermal losses, which could be as high as 50% of the heat

transmission, depending on the internal air temperature, the surface temperature of walls or windows, and the air moisture content (Moreno-Rangel 2020).

4. Airtight building envelope

Passivhaus dwellings must reach a high level of air tightness to minimise cool or heat loss due to air infiltration. Sealing construction joints and building envelope penetrations with air barriers is crucial to obtaining the requisite level of air tightness (Moreno-Rangel 2020). Thus, two required barrier layers are indicated during the design process. Firstly, airtight barriers are often positioned on a building's warm side and function as vapour barriers, shielding insulation and structures from moisture and interstitial warm air (Moreno-Rangel 2020). The other one is windshields, typically situated on the exterior of the building fabric and protect the building envelope from cold air (Moreno-Rangel 2020). Indeed, ''For Passivhaus certification the airtightness target is expressed differently as n50, which is defined as the number of air changes per hour in the building at a reference pressure differential of 50 Pascals" (McLeod, Jaggs et al. 2014).

5. Mechanical heat recovery ventilation systems

The primary reason for using a mechanical heat recovery ventilation (MVHR) system is to provide fresh air flow while optimising occupant comfort and reducing heating or cooling energy losses by recovering heat or cool from exhaust air (Moreno-Rangel 2020). Efficient ventilation with heat recovery is essential to save energy. Passivhaus buildings returned at least 75% of the heat in the exhaust air back to the outside air through a heat exchanger (PHI 2015).

To sum up, the five main elements of the Passivhaus standard are seen in Figure 4.4.

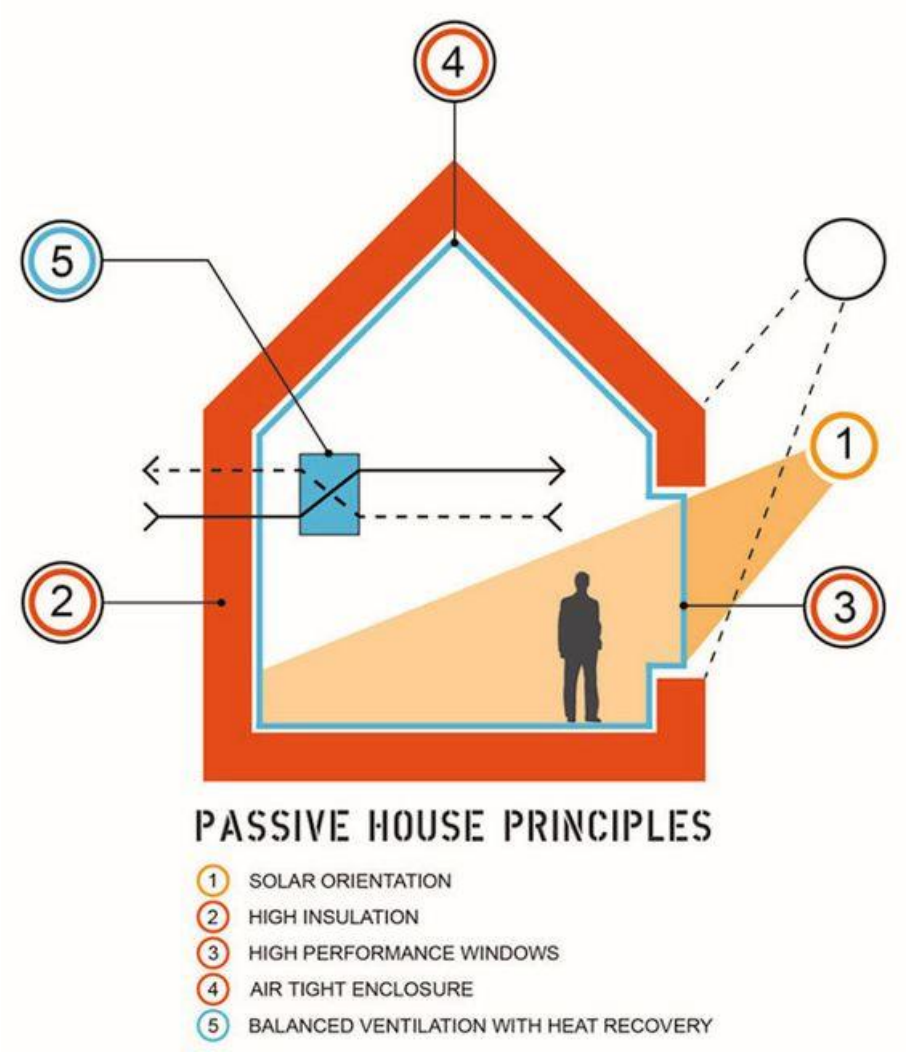


Figure 4.4. Summarising the Passivhaus Main Principles (PEDRANTI 2016)

4.1.4 Passivhaus certificates

'Passivhaus adopts a whole-building approach with clear, measured targets, focused on high-quality construction, certified through an exacting quality assurance process' *(Passivhaus Trust 2021).* The Passivhaus certification procedure was initially established for nations with continental climates, particularly Germany. The main challenge is to offset low outdoor temperatures and make the most of internal and solar heat while ensuring adequate indoor air quality (Causone, Pietrobon et al. 2017). Moreover, dehumidification and cooling in this environment are less critical, particularly in housing units (Causone, Pietrobon et al. 2017).

The Passivhaus standard has three certification categories: projects, people, and products. According to (PHI 2022), the projects standard criteria include:

1. Passive House Standard that is for new buildings,
2. EnerPHit is for retrofit construction, and
3. PHI Low Energy Building Standard which suitable for buildings which do not fully comply with Passive House or EnerPHit criteria



Figure 4.5. Passivhaus criteria (PHI 2022)

Figure 4.5 illustrates the three types of Passivhaus certification criteria. Each Passivhaus standard seal represents the level of achievement that a Passivhaus building attained.

4.1.5 Passivhaus classes

The Passivhaus standard used to have only one class of standard certification, currently known as the "Passive House classic". However, the PHI introduced two new categories named "Passive House Plus" and "Passive House Premium" when PHPP 9 was released in 2015 (PHI 2021). These classes are based on a new evaluation technique concentrating on Primary Energy Renewable (PHI 2021).

Figure 4.6 shows the Passivhaus classes for a project certification, such as Classic, Plus, and Premium, from basic certificate to the highest level. The Passivhaus certificate covers all building types, for example, residential buildings. A "premium" certificate is the top certified Passivhaus level most efficient. The premium certified facility must generate a minimum of 120 kWh/(m²a) of renewable energy, and its maximum energy usage is less than 30 kWh/(m²a) of the Primary Energy Renewable (PER). In contrast, the "classic" class is the traditional Passivhaus which uses up to 60 kWh/(m²a) of the PER. In comparison, the middle class 'plus' energy demand is limited to 45 kWh/(m²a) and has to generate at least 60 kWh/(m²a) of the PER.

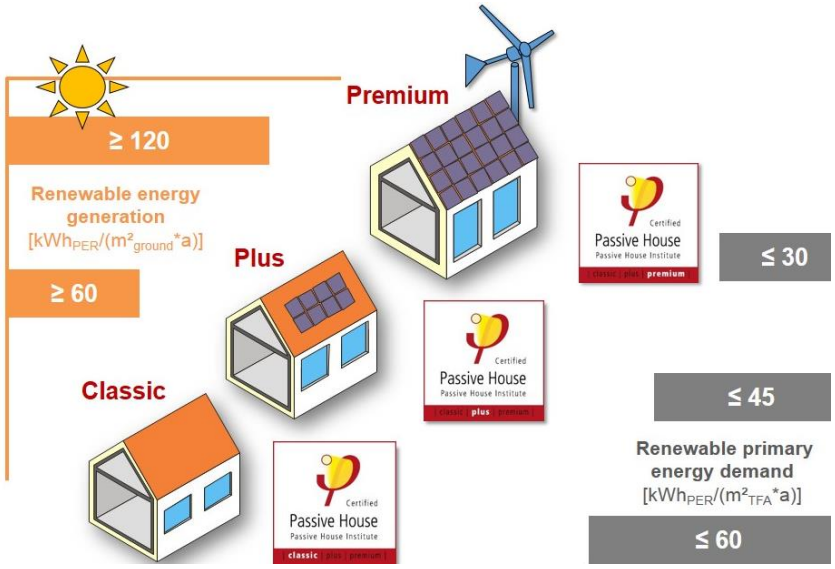


Figure 4.6. Passivhaus certification classes (PHI 2021)

The Passivhaus standard can easily be combined with on-site renewable energy production; since 2015, the new building classes "Passive House Premium" and "Passive House Plus" have been available for this supply concept (iPHA 2021).

Table 4.1. Passivhaus certification aspects for Central European climates

source (Moreno-Rangel 2020)

Passivhaus Certification Criteria (Residential)		Cool-Moderate Climate (Central European)
Specific heating demand	≤15	kWh/(m²a)
OR specific heating load	≤10	W/m²
Specific cooling demand	≤15	kWh/(m²a) + 0.3 W/(m²aK). DDH
OR specific cooling load	≤10	W/m²
AND specific cooling demand	≤4	kWh/(m²a). σe + 2 · 0.3 W/(m²aK). DDH-75 kWh/(m²a)
Specific total primary energy demand	≤120	kWh/m²/a
Airtightness n50	≤0.6	h^{-1} (@50 Pa)
Overheating frequency	10%	Percentage of time with operative temperature above 25 °C

σe Annual mean external air temperature (°C); DDH refers to Dry Degree Hours.

Table 4.1 illustrates Passivhaus standard criteria for a cool-moderate climate in central Europe. The yearly primary energy demand for cooling, heating, hot water, and electricity must not exceed 120 kWh/(m²a) or 10 W/ m² of functional living units. 15 kWh per square metre of usable living space is the maximum annual allocation for both heating and cooling demand. However, the cooling need includes an additional climate-dependent dehumidification allowance. All living areas are kept at a constant temperature of 25 degrees Celsius throughout the year, with just a 10% increase in temperature. At 50 pascals, the maximum air change rate is 0.6 per hour.

According to (Mitchell and Natarajan 2020): Treated Floor Area (TFA) is used to calculate space heating demand, excluding certain elements such as internal partitions, double-height ceilings, and any area less than 1 m in height, such as under staircases. Because annual space heating demand is divided by TFA rather than total or built floor area, maximising usable floor area within the building during the design process is encouraged (Mitchell and Natarajan 2020).

4.2 Passivhaus Software and Validation

Passive House Planning Package (PHPP) is software for verifying that a building design meets Passivhaus requirements when built according to the model (Parry 2014). In other words, Passivhaus buildings are planned, optimised and validated through PHPP (iPHA 2016). Because of that, the PHPP is an impressive design tool. However, it is simple to misunderstand the rules and end up with incorrect results; avoiding these common blunders can help you avoid having to find more energy savings later on in the project (Hines, Sally Godber et al. 2015). All constructions must use the PHPP design tool to build an accurate design model to meet the Passivhaus standard (Passivhaus Trust 2021). In 1998, the PHPP based on Excel was initially presented and had been continuously improved since then (PHI 2021). In May 2022, the Passive House Institute released the latest English Passivhaus version ten of the certification criteria, the PHPP 10 (PHI 2022). The Passivhaus standard applied to all types of buildings, including housing units. Any Passivhaus project must use the PHPP design tool following the Passivhaus requirements.

In addition, designPH is a 3D data input tool for PHPP. The designPH offers various benefits, according to (PHI 2021), including:

1. SketchUp modelling software plugins
2. 3D building envelope depiction and project data entry
3. Automatic analysis and simplified heating demand calculations
4. 3D editing and optimisation of building designs
5. Buildings envelopes geometry data can be exported to PHPP

4.3 Passivhaus Building Certification Process

Figure 4.7 depicts the procedure for obtaining a Passivhaus certificate. It displays each step necessary to acquire the PH certificate, which is divided into three stages: (1) initial check, (2) final assessment, and (3) certification processing. There are three decision makers in any proposed Passivhaus project: the designing and construction team, the Passivhaus consultant, and the Passivhaus certifier. To summarise, a Passivhaus project journey includes before and after construction.

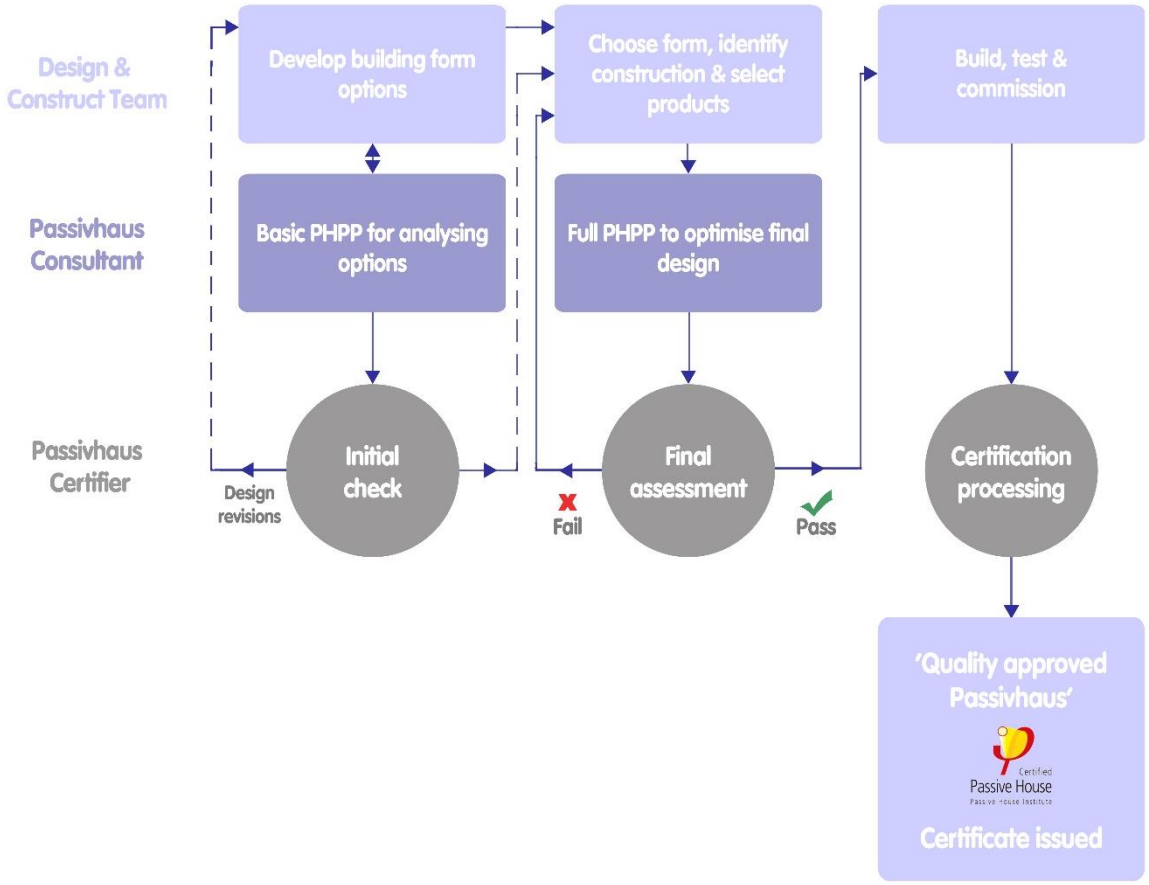


Figure 4.7. Building certification process (Passivhaus Trust 2021)

4.4 Case studies of Passivhaus Projects

There are several Passivhaus projects across the globe, for example, in the United States, Qatar (Khalfan 2017), the United Kingdom, Australia (Parry 2014), Italy (Causone, Pietrobon et al. 2017), China (Liu, Sharples et al. 2021), and the UAE (Verfasser der 2016). These successful buildings validate the energy reduction and thermal comfort improvement due to adopting the Passivhaus standard. They also had built in various climatic zones, ranging from a cold to a hot and dry climate. Meanwhile, there is a residential project in Oman named Sultan Qaboos University's Eco-house (SQU Ecohouse). This house represents one of the first research-driven efforts in Oman to design, construct, and operate an energy-efficient building through collaboration among academic, governmental, and local industrial sectors (Alalouch, Saleh et al. 2016).

Table 4.2. Locations climatic characteristics

source: (Schnieders, Feist et al. 2015)

	01—Yekaterinburg	02—Tokyo	03—Shanghai	04—Las Vegas	05—Abu Dhabi	06—Singapore
Latitude	56.8°	36.2°	31.4°	35.7°	24.4°	1.4°
Longitude	60.6°	140.4°	121.4°	−115.2°	54.7°	104.0°
Elevation	237 m	35 m	7 m	648 m	27 m	16 m
Annual average temperature	2.4 °C	13.1 °C	16.3 °C	19.8 °C	27.1 °C	27.5 °C
Max. daily average temperature	25.1 °C	28.6 °C	33.3 °C	37.0 °C	38.8 °C	30.2 °C
Average temperature Jun–Sep	14.8 °C	21.7 °C	25.9 °C	30.6 °C	33.7 °C	27.8 °C
Average daily temperature variation (max–min) Jun–Sep	9.1 K	7.5 K	6.2 K	14.6 K	13.3 K	5.7 K
Average humidity ratio Jun–Sep	7.8 g/kg	14.3 g/kg	17.2 g/kg	5.6 g/kg	17.2 g/kg	19.3 g/kg
Solar horizontal Jun–Sep	141 kW h/(m² mon)	128 kW h/(m² mon)	131 kW h/(m² mon)	225 kW h/(m² mon)	221 kW h/(m² mon)	139 kW h/(m² mon)
Solar South Jun–Sep	88 kW h/(m² mon)	63 kW h/(m² mon)	55 kW h/(m² mon)	85 kW h/(m² mon)	61 kW h/(m² mon)	54 kW h/(m² mon)
Solar E/W Jun–Sep	72 kW h/(m² mon)	63 kW h/(m² mon)	64 kW h/(m² mon)	115 kW h/(m² mon)	91 kW h/(m² mon)	68 kW h/(m² mon)
Min. daily average temperature	−26.3 °C	−2.0 °C	−0.5 °C	1.5 °C	15.5 °C	24.4 °C
Average temperature Nov–Feb	−11.0 °C	4.9 °C	7.3 °C	9.6 °C	20.6 °C	26.7 °C
Average daily temperature variation (max–min) Nov–Feb	7.7 K	12.1 K	6.8 K	11.6 K	11.5 K	5.5 K
Average humidity ratio Nov–Feb	1.5 g/kg	4.1 g/kg	5.0 g/kg	2.8 g/kg	10.1 g/kg	18.8 g/kg
Solar horizontal Nov–Feb	21 kW h/(m² mon)	76 kW h/(m² mon)	70 kW h/(m² mon)	98 kW h/(m² mon)	135 kW h/(m² mon)	134 kW h/(m² mon)
Solar South Nov–Feb	33 kW h/(m² mon)	88 kW h/(m² mon)	65 kW h/(m² mon)	134 kW h/(m² mon)	131 kW h/(m² mon)	72 kW h/(m² mon)
Solar E/W Nov–Feb	13 kW h/(m² mon)	40 kW h/(m² mon)	34 kW h/(m² mon)	59 kW h/(m² mon)	66 kW h/(m² mon)	68 kW h/(m² mon)

All temperatures are dry bulb air temperatures.

Table 4.2 summarises extensive Passivhaus study research by (Schnieders, Feist et al. 2015) that showed the climatic characteristics of various global locations. Different climatic zones of the Kingdom of Saudi Arabia are similar to some of the demonstrated cities in Table 4.2, such as Abu Dhabi and Las Vegas.

A Passivhaus project in Dubai, UAE

'The project's main goal was to verify Passivhaus standard's effectiveness in energy saving and indoor comfort – given a wide application in Dubai's real estate *market' (Verfasser der 2016).*



Figure 4.8. The Passivhaus building in Dubai, UAE (Verfasser der 2016)

In 2016, the first Passivhaus building was built in Dubai, The United Arab Emirates (UAE) (Verfasser der 2016). It was also the first Passivhaus certified project in the Middle East. The Passivhaus project shown in Figure 4.8 is an office building in Al Khawaneej, Dubai, known as Mohammed Bin Rashid Space Centre (MBRSC). According to its project documentation, the office building received a Classic Passive House certification (Verfasser der 2016).

Table 4.3 illustrates the Passivhaus building envelope structure elements and their U-value after its completion in 2016. The table shows the building's main features, such as having three-panel glazing windows, using stone wool insulation in both external wall and roof, and screeding ground floor U-value as 0.11 W/(m^2K).

Table 4.3. Envelope U-value thermal transmittance of MBRSC (Energy Plus Project 2016)

structure	description	U – value [W/(m^2K)]
external wall	stone wool in counterwall, stone wool in between the platform-frame structure, EPS EIFS	0.09
ground floor	XPS, perlite added lightweight screed	0.11
roof	stone wool in between the platform-frame structure, XPS, reflective membrane	0.08
windows	pvc frame with thermally broken reinforcements, triple pane glazing	1.1 (Uf) 0.5 (Ug) 0.28 (g)

Table 4.4 demonstrates the Classic Passive House project information. The building does not require any heating due to its location in Dubai, a hot and humid climate. In contrast, 50 kWh/(m^{2}a) is the cooling demand for the building. Dubai Passivhaus building is located in UAE, where the 'Peak summer temperatures reach 45 °C, solar radiation levels are very high, humidity ratios get as high as 20 g/kg' (Schnieders, Feist et al. 2015). Some of the main reason the building met the Passivhaus requirement is that having a unique 25 kWh electric storage feature, as shown in Table 4.4.

Table 4.4. Dubai Passivhaus Building Information

source: (Verfasser der 2016)

Year of construction/ Baujahr	2016	**Space heating / Heizwärmebedarf**	**0 kWh/(m²a)**
U-value external wall/ U-Wert Außenwand	0.076 W/(m²K) 0.090 W/(m²K)	**Space cooling / Kühlbedarf**	**50 kWh/(m²a)**
U-value basement ceiling/ U-Wert Kellerdecke	0.108 W/(m²K)	**Primary Energy Renewable (PER) / Erneuerbare Primärenergie (PER)**	73 kWh/(m²a)
U-value roof/ U-Wert Dach	0.076 W/(m²K)	**Generation of renewable energy / Erzeugung erneuerb. Energie**	185 kWh/(m²a)
U-value window/ U-Wert Fenster	0.89 W/(m²K)	**Non-renewable Primary Energy (PE) / Nicht erneuerbare Primärenergie (PE)**	143 kWh/(m²a)
Heat recovery/ Wärmerückgewinnung	89 %	Pressure test n_{50} / Drucktest n_{50}	0.48 h^{-1}
Special features/ Besonderheiten	electric storage 25kWh, water recovery from condensation drain		

In extremely hot and humid climates like Dubai, a significant portion of air conditioning energy goes toward extracting moisture from the air (latent cooling) rather than merely lowering the temperature (sensible cooling). To account for this, the Passive House Planning Package (PHPP) software calculates a specific allowance for latent demand. Consequently, the MBRSC's reported figure of 50 kWh/(m²a) reflects the combined cooling and dehumidification demand, rather than a strict threshold for rejection. Furthermore, as shown in Figure 0.10, the PHPP calculation reports a peak cooling load of just 9.7 W/m². This distinction is vital: cooling load is a peak-capacity metric, whereas annual demand is an energy-use metric. Because Passivhaus certification requires a building to meet either the annual cooling demand limit or the peak cooling load limit (≤ 10 W/m²), the building successfully achieves compliance through its peak load performance.

A Passivhaus project in Sicily, Italy

'The Botticelli project, a single family detached house located in Sicily (Italy), was conceived to assess the possibility to extend the passive house concept to the Mediterranean climate' (Causone, Pietrobon et al. 2017).

The building is a 'customized zero energy home' that is an excellent case study for the Mediterranean region's future generation of high-performance, nearly zero-energy buildings (Causone, Pietrobon et al. 2017). The house is a year-round occupied living lab created using a novel approach (Causone, Pietrobon et al. 2017). In addition, sensors and logging equipment have been installed and tuned to track the energy and comfort performance of the system under various operating situations (Causone, Pietrobon et al. 2017). This monitoring approach sets the project's results at a high level of validation. As shown in Table 4.5, the detached single-family home is 144 m^2. The main structure of the building is concrete for exterior walls and masonry for slaps, with mineral wool for thermal insulation. In conclusion, early monitoring findings demonstrate that the proposed design method effectively deals with the specific climatic circumstances (Causone, Pietrobon et al. 2017).

Table 4.5. Primary features of the Italian Passivhaus project

Source: (Causone, Pietrobon et al. 2017)

Project name	Progetto Botticelli
Location	Mascalucia (Catania) - Sicily, Italy
Building type	Detached single family house
Conditioned floor area:	144 m^2
External walls thermal transmittance	0.13 W/(m^2K)
Roof thermal transmittance	0.13 W/(m^2K)
Basement thermal transmittance	0.23 W/(m^2K)
Windows thermal transmittance	0.90 – 1.10 W/(m^2K)
Envelope air tightness (n_{50})	Lower than 0.60 volume/h
Construction type	Structural concrete and masonry, with mineral wool thermal insulation

A Passivhaus project in Qatar

In 2013, an experimental project was constructed in Barwa city, Qatar. The project is called 'Baytna', which means our house (Fahy 2013). The development has two independent villas (detached homes); one was built to Passivhaus standard. Figure 4.9 illustrates the project's exterior, which resembles an ordinary house. It also shows the solar panels on the roof and the size of windows and doors.



Figure 4.9. Baytna project, Barwa City in Qatar (Fahy 2013)

The Passivhaus project collaborates with Qatar Green Building Council (QGBC) and BARWA real estate developer (Khalfan 2019). The project objective was to test the possibility of the Passivhaus standard in Qatar's hot and dry climate (Khalfan, Sharples et al. 2015). According to the findings of a research study by (Khalfan, Sharples et al. 2015), the Passivhaus criteria may be suitable in the environment of Qatar. Moreover, another research concluded that the Qatari Passivhaus villa demanded half the total energy to run and almost a third to cool a typical housing unit, as shown in current and future situations (Khalfan 2017).

5 THE BASE CASE STUDY

5.1 Introduction

The chosen case study is a low-rise residential building in Madinah, Saudi Arabia. It goes under the umbrella of zone number one of the Saudi recommended climatic zones. This study simulates a typical first-floor flat. The same model is then applied to four additional Saudi cities. After analysing the flat performance, it would be improved to reach Passivhaus standard along with implementing the Saudi Building Code.

5.2 Building Characteristics

5.2.1 Location and Profile

The chosen residential building, classified as a low-rise building according to the SBC, is situated in the southwestern part of Madinah. It is a two-story building with two neighbouring plots of land. The main elevation is east-northern to a 15 m wide road. The southeast elevation is to an unbuilt local park currently used as parking. The land is 460 square meters, 23 m tall and 20 m wide.

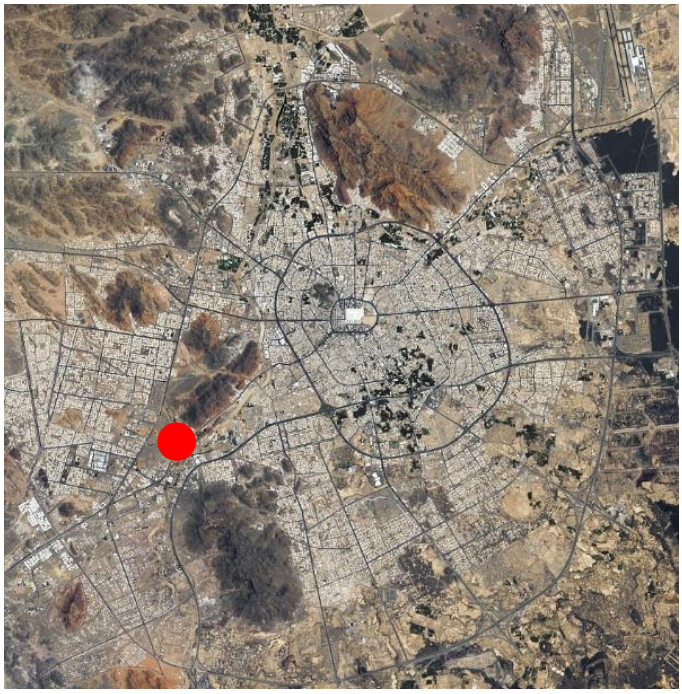


Figure 5.1. Site located in Madinah source: The Earth Observatory, NASA

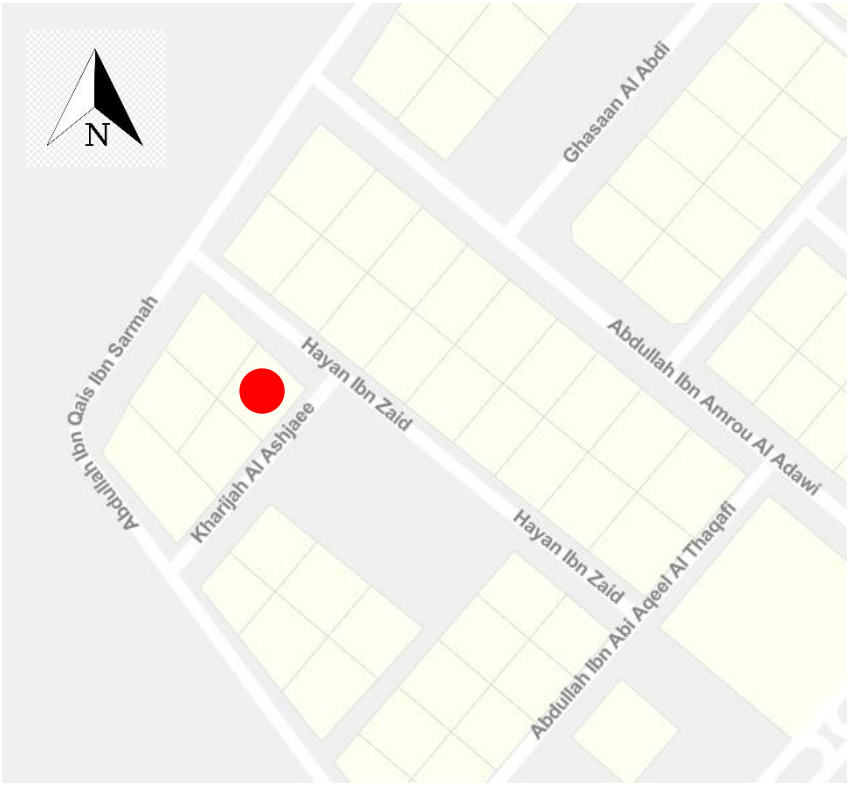


Figure 5.2. Case Study Neighbourhood in Madinah source: SPL ©2024

The structure consists of two main stories and an annexe, each floor containing only one spacious flat. The case study flat is on the first floor and comprises 240 square metres. Figure 5.2 depicts the residential building situated in the neighbourhood district in Madinah.

Table 5.1 establishes the geometric boundary conditions for the thermal model. The North-East orientation of the first floor flat minimises direct solar gain on the main façade during peak hours, whilst a modest 15.58% Window-to-Wall Ratio (WWR) limits fenestration heat transfer. These spatial characteristics provide the baseline profile for benchmarking energy performance across all evaluated climate zones.

Table 5.1 Base Case Study: Location and Profile

Category	Parameter	Exact Input Value
Location & Orientation	Location	Madinah
	Façade & Orientation	Front North-East (NE) Elevation
	Floor Level	First floor flat
Overall Dimensions	Floor Total Height	3.5 m
	Gross Floor Area	239.64 m²
	Gross Wall Area	215.68 m²
	Total Area of Windows	33.60 m²
	Window-to-Wall Ratio (WWR)	15.58 %

5.2.2 Construction and Materials

The residential building structure exemplifies the conventional construction style in Saudi Arabia, using a reinforced concrete structure comprising columns and beams and a Hordi floor slab. The wall is mainly constructed using hollow blocks of red clay or cement. A comprehensive paper by (Al-Abduljabbar, Al-Mogbel et al. 2023) for typical residential construction materials has been selected due to its validity. Table 5.2 summaries a typical construction and properties for Saudi residential building, which this research implements for the baseline model simulation input in DesignBuilder.

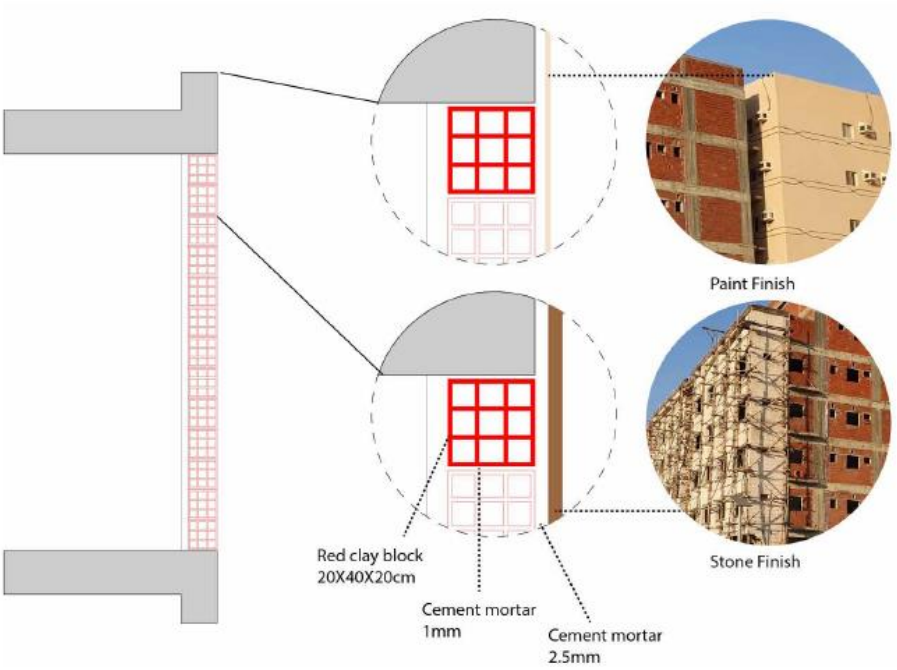


Figure 5.3. Typical Clay block construction in SA Source: (Felimban 2024)

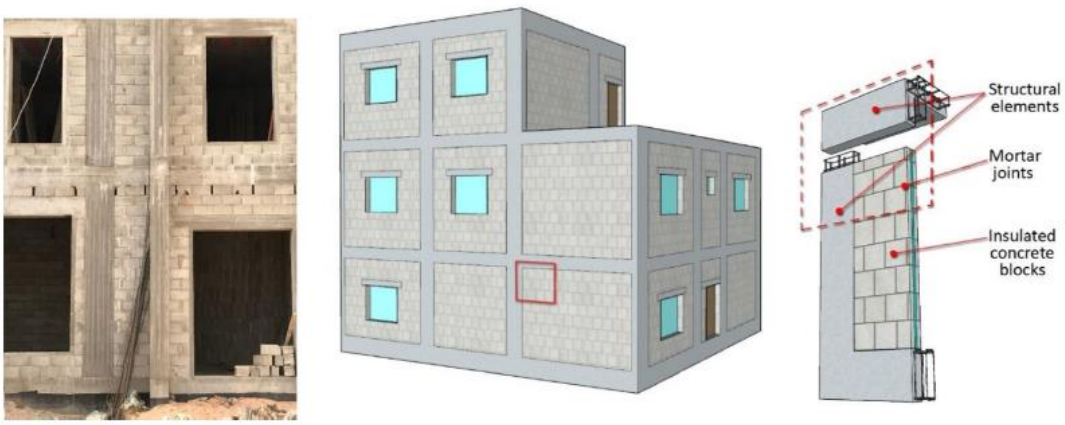


Figure 5.4. Saudi Typical Concrete Building Construction (Alayed, O'hegarty et al. 2021)

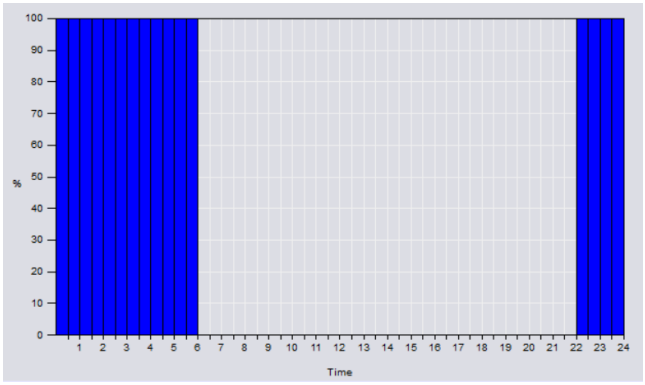
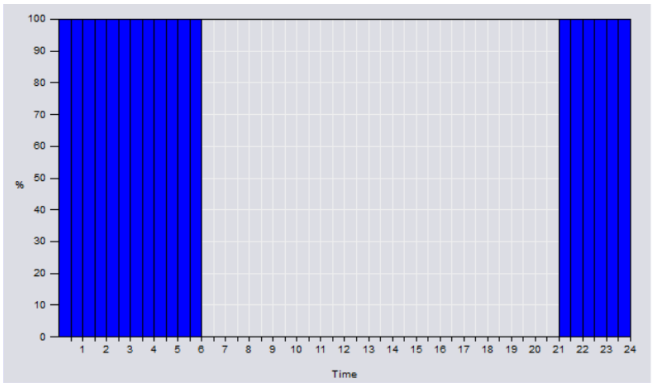
Table 5.2 Baseline Building Geometry & Characteristics

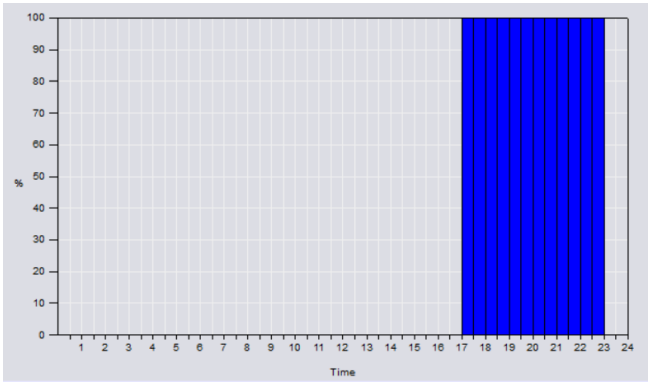
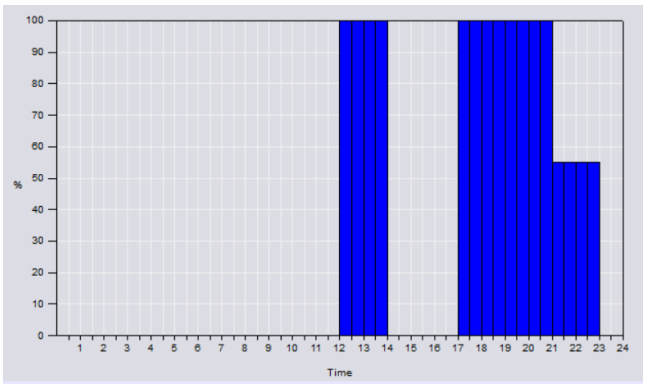
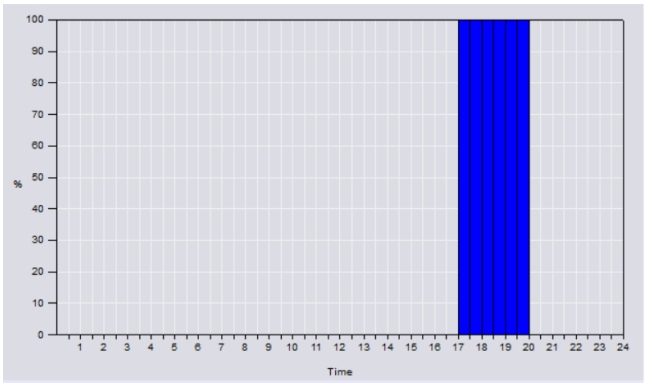
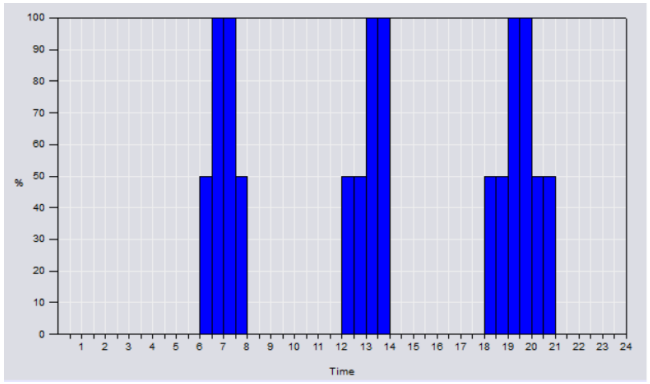
Category	Specific Component	Input Value
U-Values (Opaque)	External Wall	0.774 W/(m²K) (R-value: 1.291 m²K/W)
	Roof	1.94 W/(m²K) (R-value: 0.51 m²K/W)
Openings (Transparent)	Window Type	Single-glazed, Aluminium frame (no thermal break)
	U-Value	4.8 W/(m²K)
	SHGC	0.76
	Position	Inside
HVAC / Space Conditioning	System Type	Packaged DX AC & Split AC (no fresh air in some rooms)
	Cooling Temperature Setpoint	25°C
	Cooling System COP	0.85
	Power Source	Electricity from grid
Domestic Hot Water (DHW)	System Type	Instantaneous hot water
	DHW COP	0.85
	Power Source	Electricity from grid
Lighting	Luminaire Type	Surface mount LED
	Power Density	2.5 W/m² (100 lux)
	Radiant / Visible Fraction	0.720 / 0.180
Occupancy	Number of Occupants	5
	Metabolic Activity	Light Manual Work (Factor = 0.86)

5.3 Data Collection

Data were collected using various methods, such as official architectural drawings and actual energy consumption data, to validate the design model and simulation. The case study was simulated in DesignBuilder utilising updated hourly weather data provided by EnergyPlus. Each of the five cities features its own climatic dataset; specifically, the weather files employed for the 2023 calibration consist of Typical Meteorological Year (TMY) data. Furthermore, Table 5.3 presents the standard Saudi residential occupancy profiles applied across all simulation models.

Table 5.3 Typical Occupancy Profiles Across Investigated Cities

No.	Room Name	Occupancy Profile
1	Master Bedroom	
2	Bedrooms	

No.	Room Name	Occupancy Profile
3	Living Room	
4	Dining Room	
5	Lounge	
6	Kitchen	

5.3.1 Architectural Drawing

The architectural floor plan comprises four bedrooms, a primary living room, a dining room, a formal lounge (Majlis), a kitchen, a laundry room, and three bathrooms. Figure 5.5 illustrates the layout of the second-floor flat, located in Madinah. Furthermore, Table 5.4 details the gross wall areas, window areas, and window-to-wall ratios (%) for each of the building's elevations.

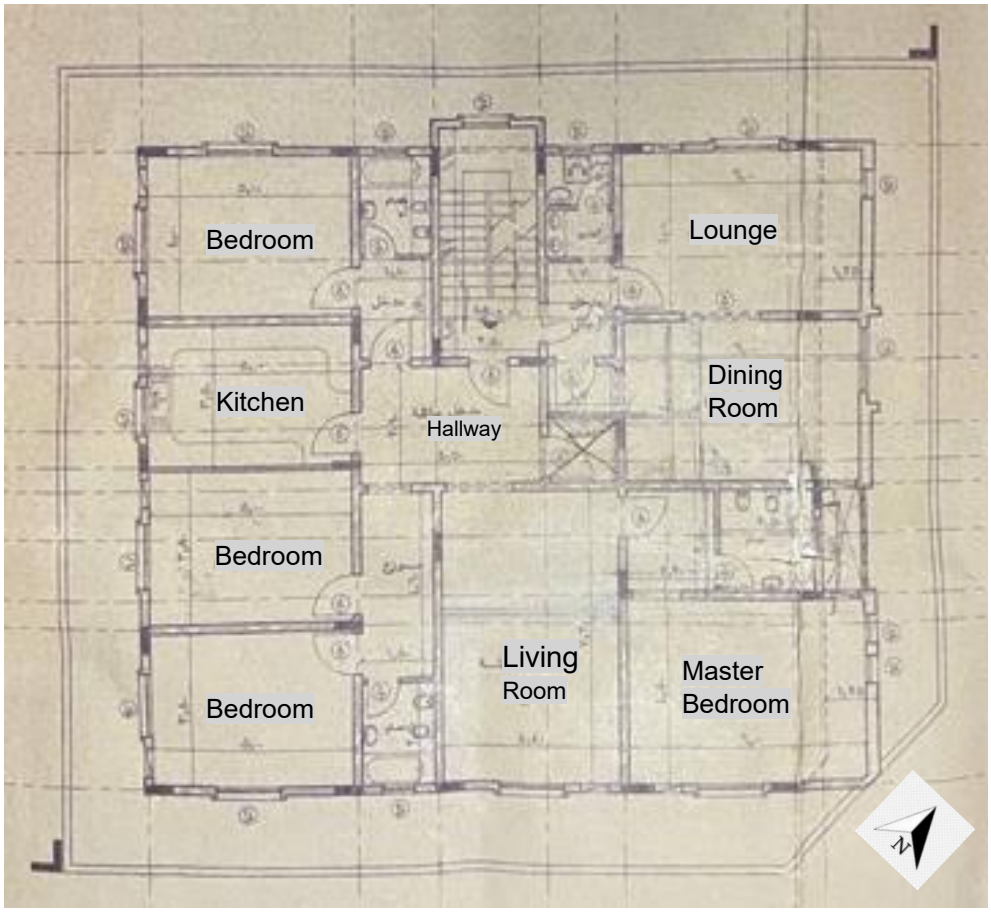


Figure 5.5. The Case Study Architectural Plan Drawing source: Architecture Office

Table 5.4 Base Case Study Elevation Profile

Parameter	North (N)	East (E)	South (S)	West (W)	Total/Average
Gross Wall Area (m²)	51.241	59.164	56.44	48.83	215.68
Window Area (m²)	8.4	8.4	9.6	7.2	33.60
Window-to-Wall Ratio (%)	16.39	14.2	17.01	14.75	15.58

5.3.2 Actual Energy Consumption

The primary energy is electricity from a grid provided by the Saudi Electrical Company (SEC). Monthly energy consumption bills are collected using the flat account profile from the SEC.

Table 5.5 illustrates the monthly electricity usage for four years between 2020 and 2023. The average energy consumption is about 33,000 kWh; however, electricity demand has increased over the years, which may reflect users' activity demands and changes in residents' age, contributing to the continuous rise in energy consumption. In general, the energy utilization has increased steadily over time. A deep decreased in May 2021 likely due to a family holiday. For this study, the recent year of 2023 annual energy consumption have been simulated.

Table 5.5. Monthly and Annual Electricity Consumption for Madinah Case

Month/Year	2020	2021	2022	2023	Average
January	834	823	685	735	769
February	839	962	1,271	1,027	1,025
March	1,985	1,907	2,099	1,505	1,874
April	2,749	2,701	3,015	2,315	2,695
May	4,434	*1,558	4,686	4,221	3,725
June	4,604	4,503	4,771	4,729	4,652
July	4,403	4,582	5,117	5,315	4,854
August	4,199	4,943	4,178	5,464	4,696
September	3,553	4,220	3,812	5,050	4,159
October	2,010	2,815	2,374	2,929	2,532
November	1,093	1,294	1,387	1,882	1,414
December	696	863	624	808	748
Total	31,399	31,171	34,019	35,980	33,142

* The sharp decrease in May 2021 is attributed to reduced occupancy during a family holiday.

Between 2020 and 2023, the dataset demonstrates both a steady annual growth and a pronounced seasonal cycle that reflects underlying fluctuations in activity. At the annual level, totals increased from 31,399 in 2020 to 35,980 in 2023, with 2021 showing only a marginal decline compared with 2020 before growth resumed in 2022 and 2023. The four-year mean of 33,142 therefore indicates that the later years consistently performed above average, while the earlier years remained slightly below. Such an upward trajectory suggests that the system under study is gradually expanding in scale or intensity, albeit with minor annual fluctuations.

Based on actual data from the monthly energy bills, Figure 5.6 depicts the Madinah apartment's electricity consumption in 2020, 2021, 2022, and 2023, along with the average energy consumption for the four years.

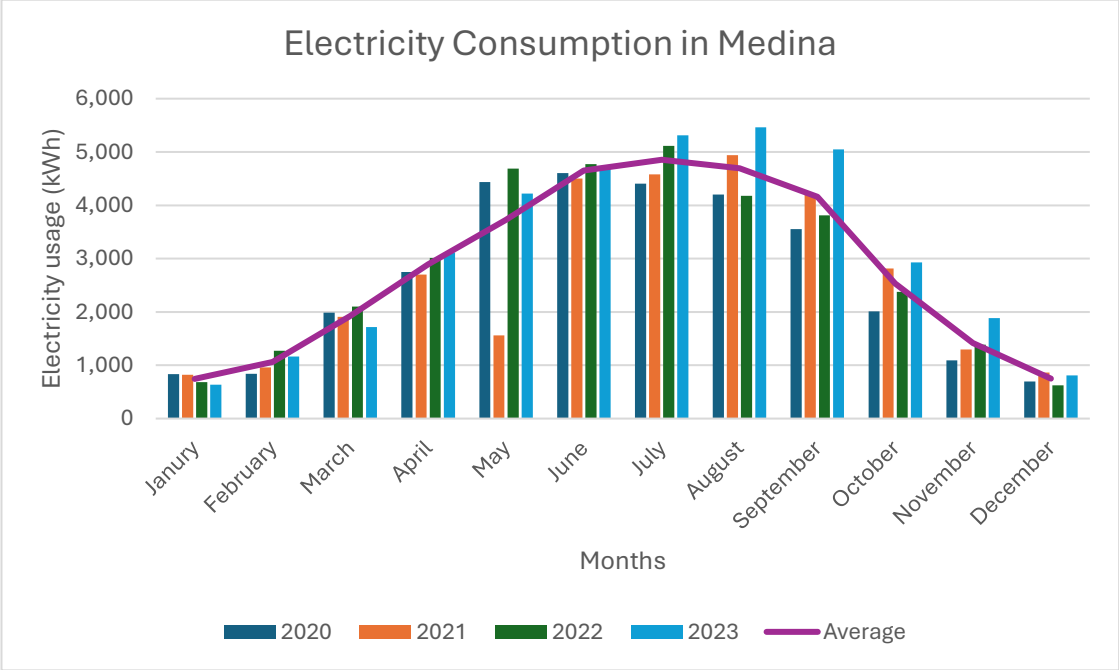


Figure 5.6. Collected Monthly Bills from SEC of the Case Study

When disaggregated monthly, a clear seasonal cycle emerges. The winter months of December to February record the lowest values, with December averaging only 748 and January 769, both considerably below the overall monthly mean of 2,762. This pattern indicates that winter is consistently the least active period, likely reflecting cyclical or climatic factors that suppress activity. By contrast, the summer months of June, July, and August consistently exceed 4,000, confirming their role as the annual peak season. June is particularly stable, ranging narrowly between 4,503 and 4,771

across the four years and producing an average of 4,652, which demonstrates its reliability as a consistently high-performing month. July and August display a stronger upward trend, culminating in August 2023 reaching 5,464, the highest single monthly figure across the entire dataset. This finding highlights not only the dominance of the summer peak but also its potential to set new record levels in future years.

The spring months of March to May represent a transitional growth phase, with March averaging 1,874 and April 2,695, before reaching a seasonal peak in May. However, the sharp decline observed in May 2021, with a value of only 1,558 compared with over 4,200 in surrounding years, constitutes a notable anomaly that significantly reduces the four-year average for that month. This irregularity suggests the presence of external or exceptional factors influencing performance in that year. Autumn months show a gradual decline from the summer peak, with September and October remaining relatively strong at 4,159 and 2,532 respectively, before a marked reduction in November with average 1,414. Such a decline points to the cyclical winding down of annual activity as the system transitions into the winter low season.

Overall, these findings indicate a consistent annual rhythm characterised by subdued winter activity, a sharp spring increase, a dominant summer peak, and a gradual autumn decline. Importantly, 2023 not only produced the highest annual total but also the absolute monthly maximum in August, whereas December 2022 marked the lowest monthly point across the four-year period. This divergence between seasonal extremes underlines the need to account for temporal variability when analysing long-term trends, as the data highlight both predictable cyclical behaviour and occasional anomalies that may carry broader implications for planning, forecasting, and policy considerations.

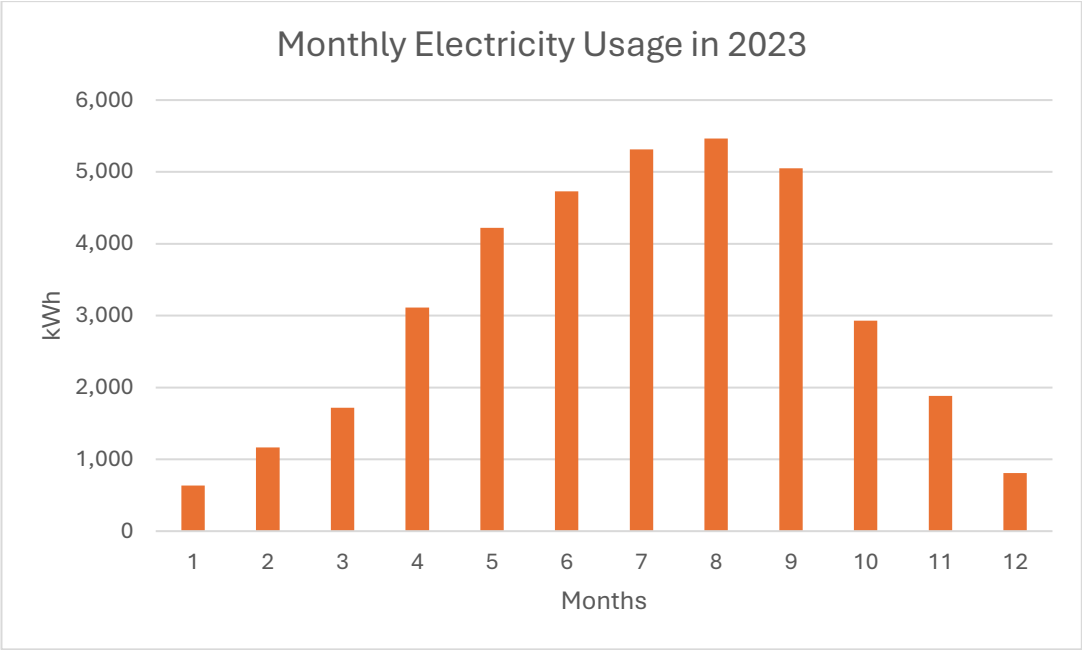


Figure 5.7. Base Case Study Energy Consumption in 2023

Figure 5.8 illustrates the operational energy breakdown for the baseline model in Madinah. Space cooling constitutes most of the energy consumption at 82%, reflecting the severe thermal demands of the local climate. Interior equipment accounts for 15%, whilst interior lighting and water heating contribute minimally at 3% and 0%, respectively.

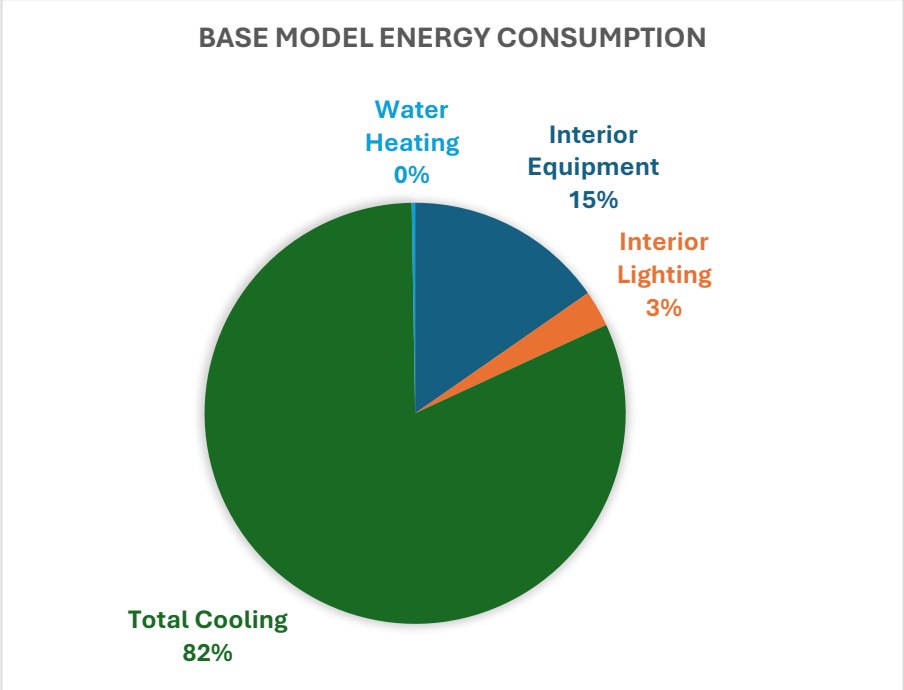


Figure 5.8. Madinah's Baseline Performance Study in 2023

5.4 Modelling and Simulation

This study describes the outcomes of various simulations conducted to determine the energy and thermal performance of the case base under multiple scenarios. The paper provides an overview of the architectural design, the history of the initial construction, the lighting and cooling system, and the energy consumption of the apartment. Validation and the possibility of improvement are the objectives of modelling and simulation. The investigation employs a performance-based strategy, a statistical testing plan, SBC and the Passivhaus standard.

Utilising modelling and simulation tools enables the evaluation of building performance under various conditions, while incorporating measured data facilitates an understanding of its long-term operational behaviour across differing climates (Energy House 2.0 2023). The flat-modelled construction properties present the typical Saudi residential building applied to the base model. Also, the zone 1 requirement is implemented as required by the SBC. The U-value for all three climate zones is described in a recent study (Alardhi, S Alaboodi et al. 2022). Building energy analysis aims to assess energy consumption efficiency, compare different systems, and identify improvement opportunities (Abu Bakar, Hassan et al. 2015). Data analysis and interpretation will be performed to determine the building envelope performance, energy consumption, and efficiency of the selected apartment.

5.4.1 Model Setup in DesignBuilder

Building energy modelling (BEM) is widely recognised as a fundamental analytical framework for the rigorous assessment of energy efficiency in residential buildings. For this reason, model calibration is a critical stage in the modelling process, as it enhances the reliability and confidence in the results (Cui, Zhu et al. 2022).

The selection of appropriate modelling software is a fundamental step in establishing a reliable simulation framework. (Alyami 2022) provides a comprehensive account of this process, highlighting the suitability of DesignBuilder for building energy modelling applications. Accordingly, the housing unit was modelled in DesignBuilder, as shown in Figure 5.9.

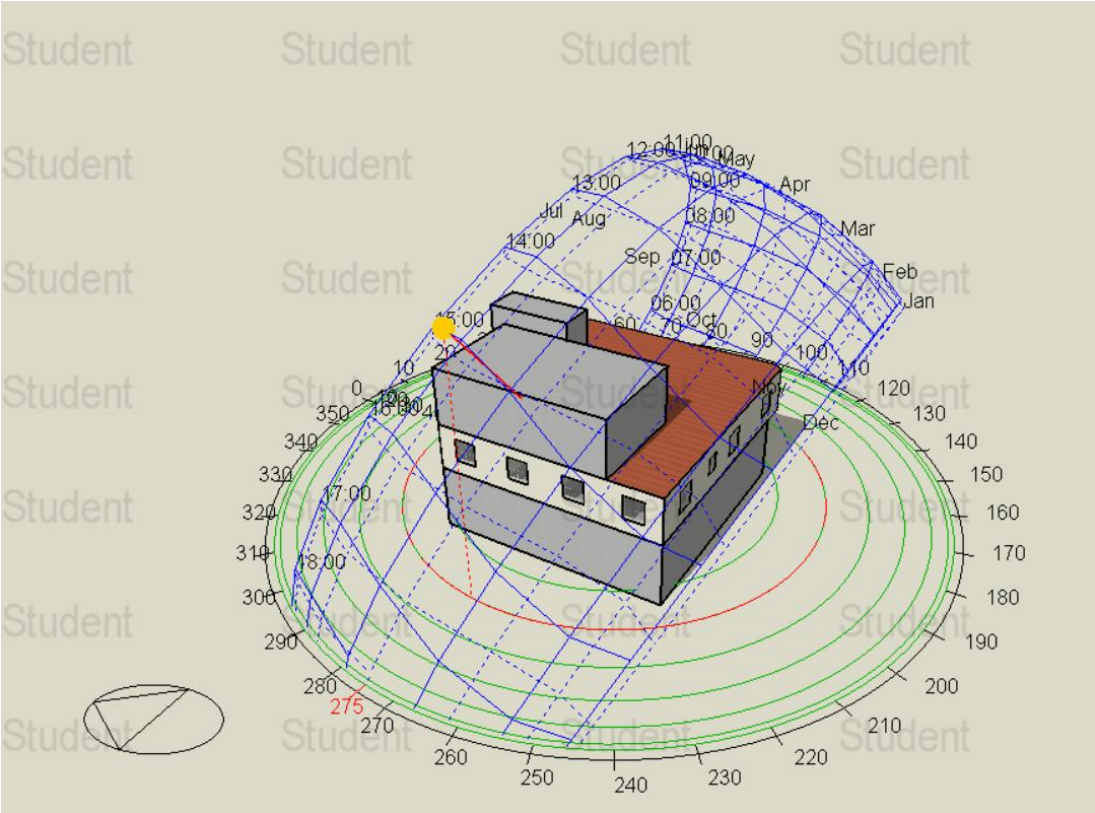


Figure 5.9 The Baseline Model in DesignBuilder

5.4.2 Baseline Model Validation and Calibration

The base case model was calibrated against the actual electricity bills for the study flat in Madinah during the year 2023. The calibration process followed the recommendations of ASHRAE Guideline 14-2014 (ASHRAE 2014) and the International Performance Measurement and Verification Protocol (Cowan 2002, Akinsooto, De Canha et al. 2014) which specify the use of Normalised Mean Bias Error (NMBE) and the Coefficient of Variation of the Root Mean Square Error (CV(RMSE)) as the principal indicators of accuracy (Ruiz and Bandera 2017). In addition, the coefficient of determination (R^2) is also calculated as supplementary indicator of model performance (Ruiz and Bandera 2017, Cui, Zhu et al. 2022). The measured data were derived from monthly electricity bills, while the simulated data were obtained from the DesignBuilder model using actual 2023 hourly weather data for Madinah. To sum up, the key uncertainty metrics employed in this validation are the Normalised Mean Bias Error (NMBE), the Coefficient of Variation of the Root Mean Square Error (CV(RMSE)), and the coefficient of determination (R^2).
The statistical measures are defined as follows: (Ruiz and Bandera 2017)

$$NMBE = \frac{1}{\bar{m}} \cdot \frac{\sum_{t=1}^{n} (m_t - s_t)}{n - p} \times 100 \ (\%)$$

$$CV\,(RMSE) = \frac{1}{\bar{m}} \sqrt{\frac{\sum_{t=1}^{n} (m_t - s_t)^2}{n - p}} \times 100 \ (\%)$$

$$R^2 = \left(\frac{n \cdot \sum_{t=1}^{n} m_t \cdot s_t - \sum_{t=1}^{n} m_t \cdot \sum_{t=1}^{n} s_t}{\sqrt{\left(n \cdot \sum_{t=1}^{n} m_t^2 - \left(\sum_{t=1}^{n} m_t\right)^2\right) \cdot \left(n \cdot \sum_{t=1}^{n} s_t^2 - \left(\sum_{t=1}^{n} s_t\right)^2\right)}} \right)^2$$

Table 5.6. Actual and Estimated Monthly Electricity Consumption

Month	Energy Consumption (kWh)		Difference (kWh)	Difference (%)
	Measured Bills	DB Simulated		
January	735	724	+10.8	+1.5%
February	1027	838	+188.6	+18.4%
March	1505	1900	-395.3	-26.3%
April	2315	2501	-186.3	-8.0%
May	4221	4292	-71.0	-1.7%
June	4729	5367	-637.8	-13.5%
July	5315	5246	+69.3	+1.3%
August	5464	5375	+89.1	+1.6%
September	5050	4928	+122.0	+2.4%
October	2929	3493	-563.6	-19.2%
November	1882	1543	+338.6	+18.0%
December	808	807	+0.6	+0.1%
Total	35980	37015	-1,035.3	-2.9%

* Positive = measured > simulated (under-prediction); Negative = simulated > measured (over-prediction).

The statistical indicators obtained are:

- NMBE = -2.88%
- CV(RMSE) = 10.09%
- R^2 = 0.975
- $\tilde{m}$ = 2998.33 kWh

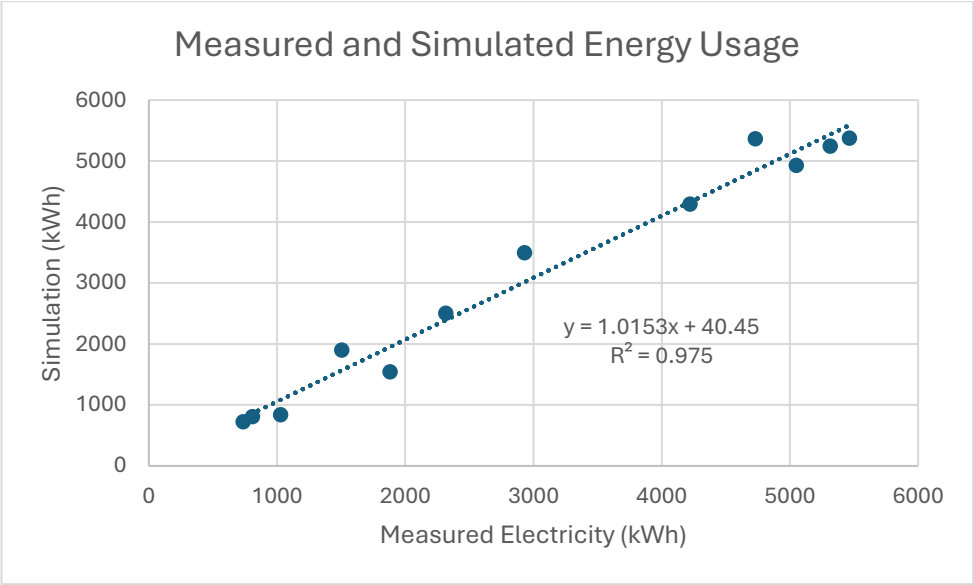


Figure 5.10. Base Model Electricity Bills and DesignBuilder Simulation Result

The predication error analysis serves as a critical indicator of how closely the simulation results reflect the actual measured electricity bills. A positive residual value indicates that measured energy consumption exceeds simulated output, signifying that the model has under-predicted energy demand. Conversely, a negative residual value reveals that simulated consumption is higher than what was measured, suggesting an over-prediction by the model. In this assessment, the most pronounced over-predictions occurred in June (-637.8 kWh, -13.5%) and October (-563.6 kWh, -19.2%), both of which correspond to transitional or high-cooling demand periods. In contrast, the most significant under-predictions were observed in November (+338.6 kWh, +18.0%) and February (+188.6 kWh, +18.4%). Despite these monthly discrepancies, the model exhibited robust overall agreement with the utility bills, displaying an annual deviation of only -1,035 kWh (-2.9%). This is well within the ASHRAE Guideline 14 acceptance thresholds (ASHRAE 2014), which require the Mean Bias Error (MBE) to be within ±5% and the Coefficient of Variation of the Root Mean Squared Error (CVRMSE) to be within ±15% for monthly data, affirming the model's reliability for energy performance assessment. R^2 is 'limited to between 0.00 and 1.00 where the upper value means that the simulated values match the measured ones perfectly and the lower ones do not' (Ruiz and Bandera 2017). Indeed, the base case model is considered adequately validated against the actual 2023 electricity bills for Madinah. This provides confidence in its subsequent application for Passivhaus adaptation scenarios across the selected Saudi cities, optimisation, and sensitivity analyses.

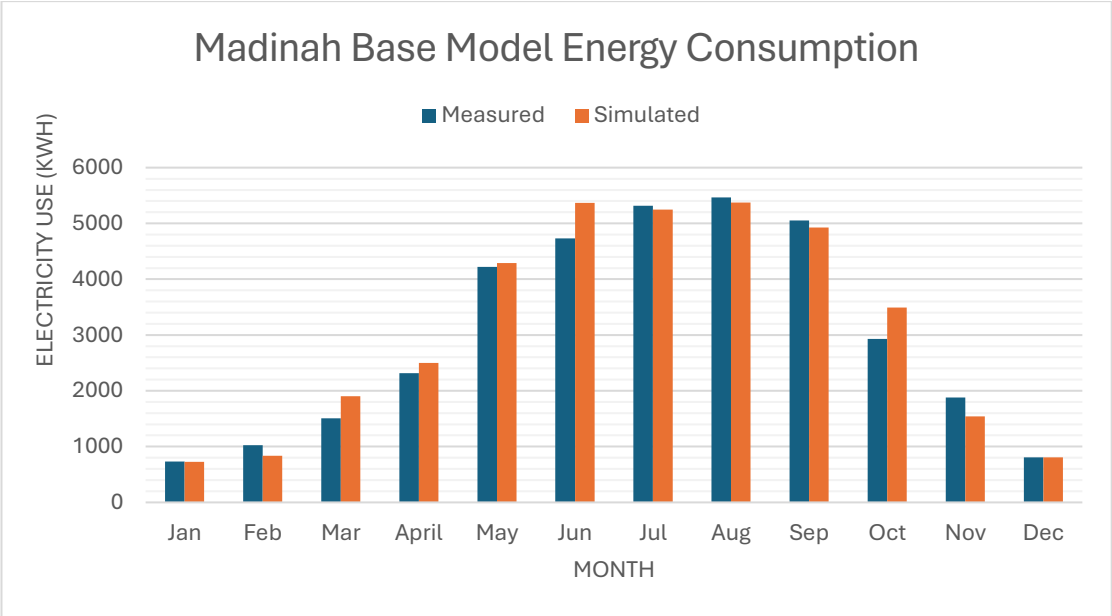


Figure 5.11. Comparing Utility and Simulated Monthly Electricity Use in 2023

5.4.3 Base Model in other cities

This stage to build a foundation base model for all the selected cities. The base case model developed for Madinah was systematically adapted to the other four cities such as Riyadh, Dammam, Tabuk, and Abha. This stage establishes a consistent foundation across the selected climatic zones by replicating the same apartment geometry, construction details, and operational schedules, while varying only the climatic conditions through the corresponding weather files. The resulting base models provide a benchmark for cross-city comparison of energy performance and prepare the ground for subsequent stages where the Saudi Building Code and the Passivhaus Standard will be applied and evaluated. Indeed, the main base model will be carried out on the remaining four cities Riyadh, Dammam, Tabuk, and Abha.

5.5 Baseline Model Performance Analysis and Evaluation

The baseline model represents the starting point of the simulation analysis, providing a reference against which the Saudi Building Code requirements and Passivhaus criteria can be evaluated. This section presents the performance outcomes of the case study flat in Madinah, followed by a comparative assessment of the four selected cities such as Riyadh, Dammam, Tabuk, and Abha. The focus is placed on total annual energy consumption, end-use distribution, and thermal comfort performance under the prevailing climatic conditions.

Both Figure 5.12 and Figure 5.13 demonstrate the residential building model located in Madinah. The case study is the grey housing unit presented in Figure 5.12. The main elevation is the North-East façade, and to the East-West is the secondary façade.

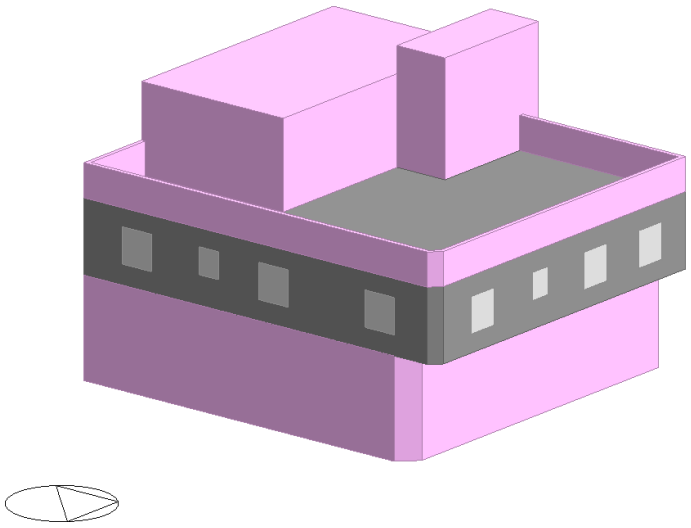


Figure 5.12. A 3-D Isometric of the Residential Building in Madinah

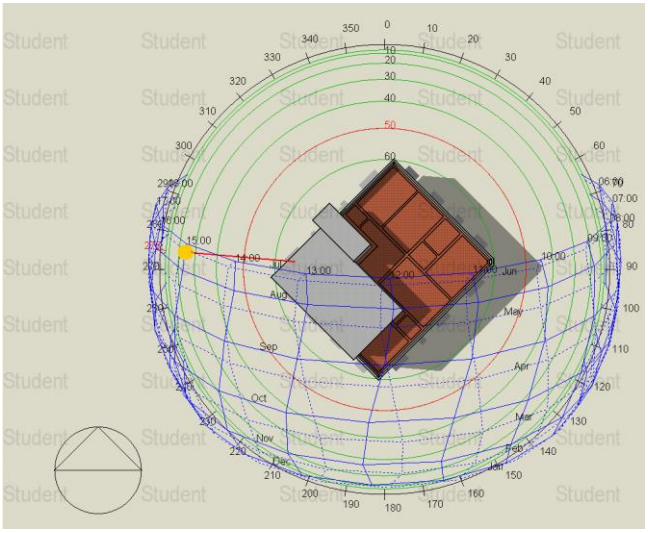


Figure 5.13 . 2-D Illustration of the Building Geometry

Table 5.7 presents the primary outcomes of the baseline model simulation in DesignBuilder. The simulated baseline study in Madinah demonstrates a total annual site energy use of 37,015 kWh, equivalent to 154.5 kWh/m² when normalised by the total floor area, and 207.4 kWh/m² relative to the conditioned area, as illustrated in Table 5.7. On the other hand, source energy is correspondingly higher, amounting to 53,478 kWh, or 223.2 kWh/m² per total floor area. These values align with typical consumption levels for residential apartments in Saudi Arabia, confirming the baseline model as a valid representation of current practice.

Table 5.7. Case Study Site and Source Energy

Category	Total Energy [kWh]	Energy Per Total Building Area [kWh/m2]	Energy Per Conditioned Building Area [kWh/m2]
Total Site Energy	37015.26	154.46	207.42
Net Site Energy	37015.26	154.46	207.42
Total Source Energy	53478.27	223.16	299.68
Net Source Energy	53478.27	223.16	299.68

Table 5.8 shows the four main categories of energy usage: total cooling, interior appliances, lighting, and heating water. A breakdown of the end-uses reveals that cooling is by far the dominant load, accounting for 30,214 kWh, according to Table 5.8. This cooling energy consumption is 81.6% of the total site energy. Interior equipment contributes 15.3%, while lighting accounts for 2.8%. Domestic hot water demand is minimal at only 0.26% of annual energy use, consistent with climatic

conditions where cooling dominates thermal loads. The negligible heating requirement reflects Madinah's hot-arid climate, in which winter temperatures remain relatively mild. The energy profile highlights the inherent inefficiency of the current envelope design, which lacks thermal insulation and relies on single-glazing windows. Consequently, the apartment is heavily dependent on mechanical cooling to maintain habitable indoor conditions during the long hot season.

Table 5.8. Simulated Energy Performance of the Madinah Case Study

Category	Energy Consumption (kWh/year)	Energy Share (%)
Total Site Energy	37015.26	100%
Interior Equipment	5672.39	15.32%
Interior Lighting	1030.87	2.78%
Total Cooling	30214.38	81.63%
District Heating (Space Heating)	0.00	0.00%
District Heating (DWH)	97.62	0.26%
Energy Use Intensity (EUI)	164.14 (kWh/m^2/year)	
Energy Per Conditioned Area	216.46 (kWh/m^2/year)	

Table 5.9 presents the simulated annual energy performance for the base case model of the residential flat located in Riyadh. The total site energy consumption is calculated to be 31,794.51 kWh per year. The most significant feature of this energy profile is the demand for cooling, which at 24,993.63 kWh/year, accounts for 78.61% of the total energy share. This single figure unequivocally identifies the cooling system as the primary driver of energy consumption within the building.

Table 5.9. Riyadh Base Model Performance in 2023

Category	Energy Consumption (kWh/year)	Energy Share (%)
Total Site Energy	31794.51	100%
Interior Equipment	5672.39	17.84%
Interior Lighting	1030.87	3.24%
Total Cooling	24993.63	78.61%
District Heating (Space Heating)	0.00	0.00%
District Heating (DWH)	97.62	0.31%
Energy Use Intensity (EUI)	132.68 (kWh/m^2/year)	
Energy Per Conditioned Area	140.06 (kWh/m^2/year)	

The second largest contributor to the energy load is interior equipment, consuming 5,672.39 kWh/year, which represents 17.84% of the total. All other end-uses are minor in comparison; interior lighting constitutes just 3.24% of the demand, while domestic water heating (DWH) is almost negligible at 0.31%. As expected for the Riyadh climate, there is no energy demand for space heating. The building's performance can also be expressed as an energy use intensity (EUI), which stands at 132.68 kWh/m²/year for the total building and 140.06 kWh/m²/year for the conditioned area. These results establish a clear and detailed energy performance baseline, demonstrating a profile entirely dominated by cooling loads, which is crucial for contextualising any subsequent analysis of energy efficiency measures.

In comparison, the Madinah baseline model consumed more energy annually at 37,015.26 kWh, with cooling comprising an even more dominant share of 81.63%. Despite this difference in magnitude, the energy profiles are fundamentally similar; both simulations show no demand for space heating. This shared characteristic highlights that cooling and equipment loads are the exclusive drivers of energy consumption in these hot-climate locations.

Table 5.10. Dammam Base Model Performance in 2023

Category	Energy Consumption (kWh/year)	Energy Share (%)
Total Site Energy	31920.39	100%
Interior Equipment	5672.39	17.77%
Interior Lighting	1030.87	3.23%
Total Cooling	25119.50	78.69%
District Heating (Space Heating)	0.00	0.00%
District Heating (DWH)	97.62	0.31%
Energy Use Intensity (EUI)	133.20 (kWh/m^2/year)	
Energy Per Conditioned Area	140.76 (kWh/m^2/year)	

The base model analysis now transitions to the distinct climatic zone of Dammam, a coastal city characterised by high humidity in addition to high ambient temperatures. This provides a critical opportunity to evaluate the base model's performance under different latent heat load conditions, with the detailed simulation results presented in Table 5.10. The model for Dammam demonstrates a total site energy consumption of 31,920.39 kWh/year, corresponding to an Energy Use Intensity (EUI) of 133.20

kWh/m²/year. While this represents a marginal increase of less than 0.5% over the inland-arid climate of Riyadh (31,794.51 kWh/year), it is a significant 13.8% lower than the 37,015.26 kWh/year demand established for the Madinah baseline. This hierarchy suggests that while regional climatic variations exist, the conditions represented by the Madinah baseline impose the most severe overall energy penalty on the archetype building.

The most insightful finding from the Dammam simulation is the remarkable consistency in the energy end-use distribution when compared to Riyadh. With cooling constituting 78.69% of the total load in Dammam, the building's energy signature is almost identical to that of Riyadh (78.61%). This suggests that despite the significant difference in humidity between the two cities, the building's operational response is similarly dominated by the demand for mechanical cooling. Other loads, such as interior equipment (17.77%) and interior lighting (3.23%), maintain a consistent and secondary role in the overall consumption profile. Furthermore, and in alignment with all previously analysed hot-climate locations, the Dammam model registers no demand for space heating, reinforcing the conclusion that the building performance challenge is exclusively one of heat rejection. This solidifies the classification of Riyadh and Dammam into a distinct cluster of energy performance, separate from the more energy-intensive Madinah baseline, and establishes that their respective inland-arid and coastal-humid environments impose a comparable operational burden on the building.

Table 5.11. Tabuk Base Model Performance in 2023

Category	Energy Consumption (kWh/year)	Energy Share (%)
Total Site Energy	23,842.79	100%
Interior Equipment	5,672.39	23.79%
Interior Lighting	1,030.87	4.32%
Total Cooling	17,041.91	71.48%
District Heating (Space Heating)	0.00	0.00%
District Heating (DWH)	97.62	0.41%
Energy Use Intensity (EUI)	99.49 (kWh/m^2/year)	
Energy Per Conditioned Area	95.50 (kWh/m^2/year)	

The investigation into climatic influence is further advanced with the introduction of the Tabuk base model, the results of which are detailed in Table 5.11. These findings represent a significant deviation from the performance patterns previously observed. Tabuk base model's total site energy consumption of 23,842.79 kWh/year, corresponding to an EUI of 99.49 kWh/m²/year, signifies a substantial reduction in demand, which about 25% lower than the Riyadh-Dammam cluster and over 35% below the Madinah baseline.

This pronounced decrease in overall consumption precipitates a notable shift in the building's energy profile. While cooling remains the largest single end-use at 71.48%, its dominance is considerably less pronounced than in the other cities. As a direct consequence, the fixed operational base loads from interior equipment and lighting become proportionally more significant, accounting for 23.79% and 4.32% of the total share, respectively. This fundamental change in the energy signature directly reflects the more temperate climate of Tabuk, which lessens the operational burden on the mechanical cooling system throughout the year. Interestingly, despite its milder climate which includes cooler winter periods, the model registered no demand for space heating, a finding consistent across all locations analysed so far. The Tabuk results, therefore, establish a new, lower benchmark for energy performance, demonstrating the profound impact of regional climate on reshaping the operational characteristics of a standardised building archetype.

Table 5.12. Abha Base Model Performance in 2023

Category	Energy Consumption (kWh/year)	Energy Share (%)
Total Site Energy	25754.19	100%
Interior Equipment	5,672.39	22.03%
Interior Lighting	1,030.87	4.00%
Total Cooling	18953.31	73.59%
District Heating (Space Heating)	0.00	0.00%
District Heating (DWH)	97.62	0.38%
Energy Use Intensity (EUI)	107.47 (kWh/m^2/year)	
Energy Per Conditioned Area	106.21 (kWh/m^2/year)	

To conclude the multi-city analysis, the base model was simulated within the distinct, high-altitude climate of Abha city, the fifth and final location investigated in this research study. As illustrated in Table 5.12, the total site energy consumption in Abha is 25,754.19 kWh/year, positioning it as the second-lowest energy user in the study, marginally above Tabuk but significantly below the demands of the other three cities. The building's energy signature in Abha closely resembles that of Tabuk; the cooling load, while still the majority at 73.59%, is considerably lower than in the hotter climates. This reduction in cooling demand elevates the proportional significance of the constant internal loads, with interior equipment and lighting constituting a combined 26.03% of the total consumption.

5.6 Summary of Key Findings

This chapter established a validated baseline model for the residential case study in Madinah, which was then used as an archetype to analyse its performance across the diverse climates of Riyadh, Dammam, Tabuk, and Abha. The core objectives were to quantify the impact of regional climate on energy performance and to establish a distinct baseline model for each city. The analysis confirms that geographic location is a primary determinant of a building's total energy consumption and its end-use distribution as illustrated in Figure 5.14.

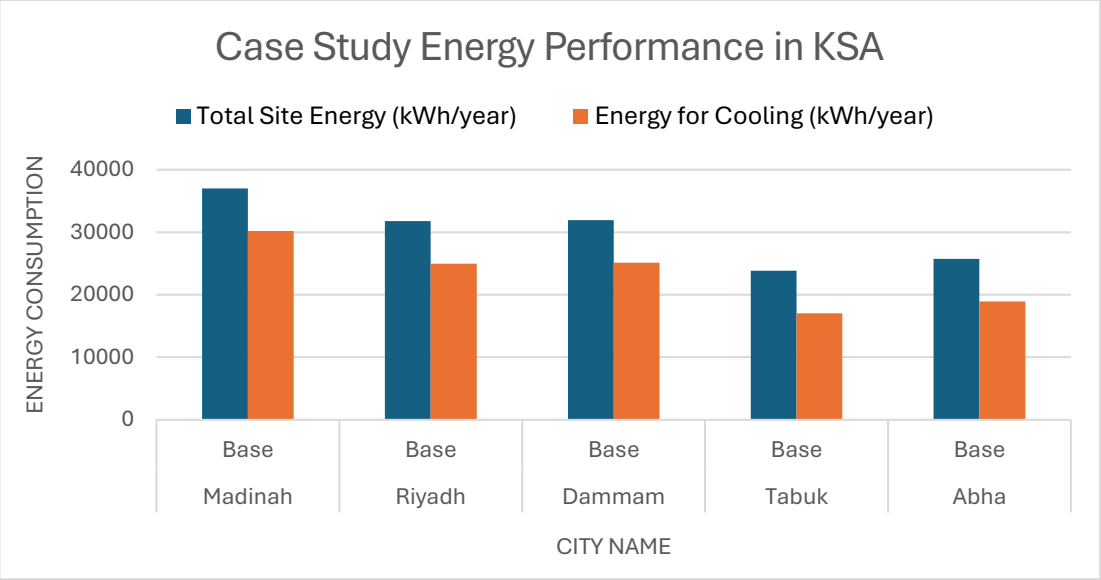


Figure 5.14 Baseline Model Simulated in Five Saudi Cities

Across all five case studies, the most consistent finding was the absolute dominance of the cooling load, which accounted for 71.5% of total energy in the mildest climate, Tabuk city, and over 81.6% in the most demanding, Madinah city. Conversely, the complete absence of any demand for space heating was a unifying characteristic, simplifying the performance challenge to one of exclusively managing heat gain.

The investigation revealed that climatic impacts grouped the cities into three distinct tiers of energy performance. Madinah established the upper benchmark at about 37,000 kWh/year. A mid-tier cluster was formed by Riyadh and Dammam, which produced remarkably similar metrics of almost 32,000 kWh/year despite their different arid and humid conditions. The third tier, representing the lowest demand, comprised Tabuk and Abha, with consumptions of almost 24,000 kWh/year and 26,000 kWh/year, respectively. This empirical clustering provides a clear, quantifiable hierarchy of climatic severity for the building archetype.

Finally, the analysis highlighted a fundamental shift in the building's energy signature in response to milder climates. As cooling demand decreased in locations like Tabuk and Abha, the constant internal loads from equipment and lighting became proportionally more significant, rising from 18% in Madinah to over 28% of the total energy share in Tabuk. The key implication is that while high-efficiency cooling is paramount everywhere, the relative importance of addressing internal base loads increases in temperate zones. This chapter has therefore successfully established five climate-specific baselines, providing an essential, empirically grounded foundation for the subsequent evaluation of energy efficiency measures.

6 APPLYING SAUDI BUILDING CODE AND PASSIVHAUS STANDARD

6.1 Introduction

This chapter utilises and assesses the practical implications of local and international standards for performance evaluation. It applies both the Saudi Building Code (SBC) and the Passivhaus Standard (PH) to the validated base case model in Madinah, extending the same procedure to four additional Saudi cities such as Riyadh, Dammam, Tabuk, and Abha, using their respective climatic scenarios. The SBC serves as a local benchmark to enable direct comparison with the Passivhaus approach. This dual application provides the basis for assessing Passivhaus suitability within Saudi Arabia's regulatory and climatic context.

Key components covered in this chapter include:

- Application of SBC compliance criteria
- Implementation of Passivhaus design measures
- Simulation process across five cities
- Summary of performance outputs for each standard

The aim is to assess the effectiveness of each standard in improving building performance and to determine the feasibility of applying the Passivhaus approach in the Saudi Arabia's various climates.

6.2 Saudi Building Code (SBC) Application

The Saudi Building Code (SBC) utilises a three-zone climatic system. For SBC purposes, Zone 1 includes Madinah, Riyadh, and Dammam; Zone 2 encompasses Tabuk; and Zone 3 encompasses Abha. This section details the code's implementation on the primary base-case study in Madinah, followed by its application to the remaining four cities. As recommended in Chapter 3, the objective of this multi-city approach is to establish a foundation model for each zone within the five-zone system defined by this thesis. The prescriptive envelope requirements for each zone and the corresponding HVAC simulation parameters are detailed in Table 6.1 and Table 6.2, respectively.

Table 6.1 Saudi Building Code Maximum Requirements (SBC 602-2018)

Category		Zone 1	Zone 2	Zone 3
External Walls	W/(m²K)	0.342	0.397	0.453
External Roofs	W/(m²K)	0.202	0.238	0.273
Windows / Triple-Glazed with aluminium frame	W/(m²K)	2.668	2.668	2.668
External Doors	W/(m²K)	2.839	2.839	2.839
SHGC		0.245	0.245	0.245
Airtightness	ACH @ 50 Pa	4 ACH	4 ACH	4 ACH

Table 6.2 SBC Model HVAC Input Values

Specific Component	Input Value
Heating Temperature Setpoint	18°C
Cooling Temperature Setpoint	22°C
Cooling System COP	3.0
Heating System COP	3.6

6.2.1 Zone One (SBC)

As defined by the Saudi Building Code, Climate Zone One encompasses the three selected cities of Madinah, Riyadh, and Dammam. The Madinah case study was modified to comply with the SBC requirements based on the Zone obligation according to the SBC 602. The analysis begins by applying the SBC's prescriptive requirements for this zone to the original Madinah baseline model.

Table 6.3 demonstrates the results of the base model after the SBC implementing in Madinah. The primary impact was a significant reduction in energy consumption, with total site energy reduced to 31,153 kWh/year, a 16% improvement compared to the original baseline consumption of 37,015 kWh/year. This finding demonstrates the effectiveness of the code's mandatory measures in enhancing the building's energy performance. Table 6.3 further details the distinction between the model's site energy (energy consumed at the building) and its source energy (energy consumed to generate and deliver power to the building).

Table 6.3. SBC Model's Site and Source Energy in Madinah

Category	Total Energy [kWh]	Energy Per Total Building Area [kWh/m2]	Energy Per Conditioned Building Area [kWh/m2]
Total Site Energy	31153	138.35	185.71
Net Site Energy	31153	138.35	185.71
Total Source Energy	49473.79	214.85	288.39
Net Source Energy	49473.79	214.85	288.39

An analysis of the energy end-uses, detailed in Table 6.4, reveals that while overall consumption decreased, the building's energy signature remains dominated by cooling. The total cooling load of 24,513 kWh accounts for 78.7% of the total energy share. This continued dominance, despite the overall savings, highlights that while Saudi Building Code (SBC) provides a crucial foundation for energy efficiency, significant loads remain that may require strategies beyond the code's minimum requirements.

Table 6.4. Madinah's SBC Modelling Subcategory Usage

Category	Energy Consumption (kWh/year)	Energy Share (%)
Total Cooling	24,513	78.70%
Interior Equipment	5,556	17.80%
Interior Lighting	991	3.20%
District Heating (DWH)	93	0.30%
Total Site Energy	31,153	100%
Performance Metrics		
Energy Use Intensity (EUI)	135 kWh/m²/year	
EUI per Conditioned Area	143 kWh/m²/year	

In conclusion, the application of the Saudi Building Code in Madinah confirms two key findings. First, the code's requirements provide a valuable improvement, reducing the model's annual energy consumption by 16%. Second, despite these savings, cooling remains the primary energy load, even in the improved case study. Together, these results establish a new, more efficient performance benchmark for Climate Zone One. The following analysis will now apply these same code requirements to the flat's base model in Riyadh and Dammam to determine their performance against this benchmark.

Continuing the examination within climate zone one, the analysis shifts to Riyadh, where the same SBC prescriptive measures were implemented on the flat's base model. This yielded a significant improvement, reducing total site energy consumption to 26,670.74 kWh/year, as illustrated in Table 6.5. This figure represents a 16% reduction from Riyadh's original pre-code baseline, 31,794 kWh/year, an efficacy rate identical to that observed in Madinah, suggesting a consistent level of effectiveness for the SBC in similarly hot and arid climates.

Table 6.5. SBC Model (Riyadh)

Category	Energy Consumption (kWh/year)	Energy Share (%)
Total Cooling	20,185.36	75.70%
Interior Equipment	5,401.89	20.30%
Interior Lighting	990.9	3.70%
District Heating (DWH)	92.59	0.30%
Total Site Energy	26,670.74	100%
Performance Metrics		
Energy Use Intensity (EUI)	115.82 kWh/m²/year	
EUI per Conditioned Area	117.70 kWh/m²/year	

However, a deeper examination reveals notable distinctions when compared to the SBC-compliant model in Madinah. While the energy signature of the Riyadh model is characterized by a substantial cooling demand at 75.7%, this proportion is discernibly lower than Madinah's 78.7%. Furthermore, the absolute energy consumption for the Riyadh flat is approximately 14% lower than the SBC-compliant Madinah model, which is 31,153 kWh/year. This distinction underscores that even within a single climatic zone, subtle regional variations in temperature and solar radiation have a pronounced impact on a building's final energy demand.

These results for Riyadh therefore add a critical layer of nuance to the analysis. They confirm the SBC is a robust tool for achieving foundational savings, yet its impact is not uniform, as the final energy consumption remains highly sensitive to the local climate. This establishes a more refined performance benchmark for Riyadh and sets the stage for the final analysis within Zone One: the coastal city of Dammam.

The final stage of the Climate Zone One analysis investigates the performance of the flat model in Dammam, introducing the variable of coastal humidity. Dammam's result, detailed in Table 6.6, demonstrates a total site energy consumption of 26,327.40 kWh/year. This represents a 17.5% reduction from Dammam's original pre-code baseline, confirming the SBC's efficacy in a hot-humid climate at a rate of improvement slightly higher than that found in the arid climates of Madinah and Riyadh.

Table 6.6. SBC Model (Dammam)

Category	Energy Consumption (kWh/year)	Energy Share (%)
Total Cooling	19,842.03	75.40%
Interior Equipment	5,401.89	20.50%
Interior Lighting	990.9	3.80%
District Heating (DWH)	92.59	0.40%
Total Site Energy	26,327.40	100%
Performance Metrics		
Energy Use Intensity (EUI)	114.33 kWh/m²/year	
EUI per Conditioned Area	116.03 kWh/m²/year	

The most insightful finding emerges when comparing the Dammam model to its counterpart in Riyadh city. Despite the significant environmental differences between Riyadh's dry heat and Dammam's pronounced humidity, their SBC-compliant performance metrics are nearly identical. Dammam's total consumption is only 1.3% lower than Riyadh's, which is 26,670 kWh/year, and their energy profiles are strikingly similar, with cooling loads of 75.4% and 75.7%, respectively. This remarkable similarity suggests that for a building compliant with SBC standards, the high ambient temperature is the principal driver of energy use, largely overriding the secondary effects of humidity on the cooling system's load.

In conclusion, the analysis of SBC Climate Zone One reveals a more complex picture than the code's broad zoning implies. While applying the SBC consistently reduced total site energy by approximately 16-18% compared to the baseline across all three cities, the absolute performance outcomes illustrate a clear clustering. Madinah establishes the upper benchmark with a total site energy of 31,153 kWh/a. In contrast, Riyadh and Dammam form a distinct, lower-consumption cluster, with energy use of 26,671 kWh/y and 26,327 kWh/y respectively. This divergence is primarily driven by cooling demand, which, despite being reduced by 19-21% in all cases, remains substantially higher in Madinah (24,513 kWh/a). This demonstrates that while the SBC is effective, its application results in a tier of performance outcomes that are sensitive to local climatic subtleties within the same zone. This refined understanding concludes the investigation into Zone One.

The simulation results for the three cities representing SBC Zone One such as Madinah, Riyadh, and Dammam, are summarised and compared in the tables below.

Table 6.7. Simulated Energy Performance: Baseline vs. SBC Models in Madinah

Category (kWh)	SBC Modelling	Base Case Study	Difference	%
Total Site Energy	31153	37015	5862.13	-15.84%
Total Cooling	24513	30214	5700.75	-18.87%
Interior Equipment	5556	5672	115.86	-2.04%
Interior Lighting	991	1031	40.1	-3.89%
District Heating [water]	93	98	5.41	-5.52%
Performance Metrics (kWh/m²/year)				
Energy Use Intensity (EUI)	135	164.14	29.14	-17.75%
EUI per Conditioned Area	143	216.46	73.46	-33.94%

Table 6.8. Simulated Energy Performance: Baseline vs. SBC Models in Riyadh

Category (kWh)	SBC Model	Base Model	Difference	%
Total Site Energy	26,671	31,795	5124.26	-16.12%
Total Cooling	20,185	24,994	4808.64	-19.24%
Interior Equipment	5,402	5,672	270.11	-4.76%
Interior Lighting	991	1,031	40.1	-3.89%
District Heating [water]	93	98	5.41	-5.52%
Performance Metrics (kWh/m²/year)				
Energy Use Intensity (EUI)	115.82	132.68	16.86	-12.71%
EUI per Conditioned Area	117.70	140.06	22.36	-15.96%

Table 6.9. Simulated Energy Performance: Baseline vs. SBC Models in Dammam

Category (kWh)	SBC Model	Base Model	Difference	%
Total Site Energy	26,327	31,920	5592.6	-17.52%
Total Cooling	19,842	25,120	5277.97	-21.01%
Interior Equipment	5,402	5,672	270.11	-4.76%
Interior Lighting	991	1,031	40.1	-3.89%
District Heating [water]	93	98	5.41	-5.52%
Performance Metrics (kWh/m²/year)				
Energy Use Intensity (EUI)	114.33	133.20	18.87	-14.17%
EUI per Conditioned Area	116.03	140.76	24.73	-17.57%

6.2.2 Zone Two (SBC)

Tabuk city is the selected representative for this zone. Proceeding to the temperate climate of Tabuk, the application of the Saudi Building Code resulted in a total site energy consumption of 19,450 kWh/year, as illustrated in Table 6.10. This notable outcome represents an 18.4% reduction from the original baseline, the most substantial percentage improvement observed thus far. The primary driver for this saving was a 23.6% decrease in the annual cooling load, confirming the code's effectiveness in improving the building envelope's thermal performance.

Table 6.10. SBC Model for Tabuk City

Category	Energy Consumption (kWh/year)	Energy Share (%)
Total Cooling	13,007	66.90%
Interior Equipment	5,359	27.60%
Interior Lighting	991	5.10%
District Heating (DWH)	93	0.50%
Total Site Energy	19,450	100%
Performance Metrics		
Energy Use Intensity (EUI)	81.0 kWh/m²/year	
EUI per Conditioned Area	73.0 kWh/m²/year	

Furthermore, this substantial reduction in cooling load precipitated a notable shift in the building's energy signature. As detailed in Table 6.10, the share of total energy consumed by cooling fell to 66.9%, down from 71.5% in the baseline model. Consequently, the proportional significance of internal loads increased, with the combined share of equipment (27.6%) and lighting (5.1%) constituting nearly a third of total consumption. This indicates that as the Saudi Building Code mitigates thermal loads, strategies targeting the efficiency of internal equipment become increasingly critical for achieving further savings in milder climates. Table 6.11 presents a comparison of the energy consumption metrics for Tabuk.

Table 6.11. Simulated Energy Performance: Baseline vs. SBC Models in Tabuk

Category (kWh)	SBC Model	Base Model	Difference	%
Total Site Energy	19,450	23,843	4392.68	-18.42%
Total Cooling	13,007	17,042	4034.49	-23.67%
Interior Equipment	5,359	5,672	313.19	-5.52%
Interior Lighting	991	1,031	40.1	-3.89%
District Heating [water]	93	98	5.41	-5.52%

6.2.3 Zone Three (SBC)

The analysis of the Saudi Building Code (SBC) application culminates with Zone Three, represented by the unique high-altitude climate of Abha.

Table 6.12. Abha SBC Scenario Simulation

Category	Energy Consumption (kWh/year)	Energy Share (%)
Total Cooling	9,648.71	59.20%
Interior Equipment	5,556.14	34.10%
Interior Lighting	990.9	6.10%
District Heating (DWH)	92.59	0.60%
Total Site Energy	16,288.33	100%
Performance Metrics		
Energy Use Intensity (EUI)	70.73 kWh/m²/year	
EUI per Conditioned Area	56.24 kWh/m²/year	

The simulation results for this city, detailed in Table 6.12, reveal the most profound energy performance improvements of this study. The total site energy consumption for the Abha flat model was reduced to 16,288 kWh/year. This represents a remarkable 36.7% reduction from its original baseline (25,754 kWh/year), a saving nearly double that achieved in the hotter climates of Zone One. This substantial improvement is primarily driven by an almost 50% decrease in the specific cooling load. Indeed, this energy reduction illustrates the powerful impact of the SBC's thermal regulations, particularly in a mild climate where the building envelope is the principal performance variable.

The reduction in cooling demand fundamentally reshapes the building's energy profile, marking a paradigm shift in its operational characteristics. For the first time, the cooling load's share of total energy drops significantly, accounting for just 59.2% of the energy consumption, as shown in Table 6.12. Consequently, the non-climatic internal loads become exceptionally prominent; the combined share of interior equipment (34.1%) and lighting (6.1%) constitutes over 40% of the building's total energy use. This critical finding implies that for an SBC-compliant building in a climate like Abha, the energy efficiency challenge is no longer dominated by cooling. Instead, the problem becomes a near-even split between thermal performance and internal plug loads, making strategies that target appliance efficiency and occupant behaviour just as vital as those for the building envelope.

Table 6.13. Simulated Energy Performance: Baseline vs. SBC Models in Abha

Category (kWh)	SBC Model	Base Model	Difference	%
Total Site Energy	16288.33	25754.19	9465.86	-36.75%
Total Cooling	9648.71	18953.31	9304.6	-49.09%
Interior Equipment	5556.14	5672.39	116.25	-2.05%
Interior Lighting	991	1,031	40.1	-3.89%
District Heating [water]	93	98	5.41	-5.52%

Table 6.13 presents the simulated energy performance comparison between the Base and SBC models in Abha, demonstrating an overall total site energy reduction of almost 37%. The primary driver of these energy savings is space cooling, which dropped significantly by 49.09%. In contrast, non-thermal end-uses such as interior equipment, lighting, and hot water heating experienced modest reductions.

6.3 Implementing the Passivhaus (PH)

This section details a quantitative analysis of applying the Passivhaus (PH) standard to the representative residential building in Saudi Arabia. The study uses dynamic thermal simulation to assess the standard's effectiveness against baseline models representing typical pre-code construction practices. The investigation was based on baseline simulation models and their corresponding Passivhaus models for Madinah, Riyadh, Dammam, Tabuk, and Abha. Each Passivhaus model was a systematic upgrade of its baseline, retrofitted with key modifications such as continuous high-performance insulation, an airtight envelope, triple-glazed windows, thermal bridge-free detailing, and a mechanical ventilation system. The analysis begins with a detailed case study in Madinah, followed by a comparative assessment across the other four selected cities. The objective is to quantify the energy performance gains from the Passivhaus standard and evaluate its suitability across the Kingdom's diverse climatic zones. Table 6.14 outlines the specific material properties and mechanical efficiencies integrated into the Passivhaus model.

Table 6.14 Passivhaus Model Input Specification

Category	Specific Component	Input Value
U-Values (Opaque)	External Walls	0.15 W/(m²K)
	Roof	0.15 W/(m²K)
U-Values (Transparent)	Windows / Triple-Glazed with krypton gas and aluminium frame	0.598 W/(m²K)
	External Doors	0.85 W/(m²K)
Total Solar Transmission	SHGC	0.245
Airtightness	Infiltration Rate (n50)	0.6 ACH @ 50 Pa
Ventilation (MVHR)	Heat Recovery Efficiency	90%
Thermal Bridging	Assumed Linear Transmittance (Ψ)	0.01 W/(mK)
HVAC / Space Conditioning	Heating Temperature Setpoint	18°C
	Cooling Temperature Setpoint	23°C
	Cooling System COP	4.0
	Heating System COP	3.6

6.3.1 Primary Case Study: Madinah (Zone One)

The foundational analysis was conducted on the model situated in Madinah, one of the most demanding thermal environments in the study. The key performance indicators for both the baseline and Passivhaus models are presented in Table 6.15.

Table 6.15. Comparison of Madinah's PH and Baseline Model

Energy Category	Base Model	PH Model	Reduction (%)
Total Site Energy (kWh/year)	37015	27905	-24.61
Total Site Energy (kWh/m²/year)	154	124	-19.65
Cooling (kWh/year)	30214	21823	-27.77
Interior Equipment (kWh/year)	5672	5213	-8.09
Interior Lighting (kWh/year)	1031	772	-25.15
District Heating for Water (kWh/year)	98	97	-0.61
Energy Per Conditioned Area (kWh/m²/year)	169	128	-25.00

The simulation for Madinah demonstrates the significant impact of the Passivhaus standard in a hot climate. The most critical finding is the substantial reduction in cooling energy, which decreased from 30214 kWh/a to 21823 kWh/a, representing nearly a 28% energy saving. This highlights the effectiveness of the 'fabric-first' approach in minimising unwanted solar and thermal gains.

This improved thermal performance is the main driver behind the decrease in the building's overall energy use intensity, which fell from 169 kWh/m²a to 128 kWh/m²a, a 25% reduction. This confirms that the holistic application of PH principles yields comprehensive energy savings. Further efficiencies were observed in interior lighting and equipment, with consumption reduced by over 25% and 9% respectively, underscoring the importance of integrating high-efficiency systems. Space heating demand was negligible in both models, with the minimal energy recorded being for domestic hot water. In summary, applying the Passivhaus standard in Madinah leads to significantly improved building performance, primarily by reducing the cooling load.

Table 6.16. Madinah PH Energy Performance

Energy Category	Energy Consumption (kWh/year)	Energy Share (%)
Total Site Energy	27905	100
Cooling	21823	78.20
Interior Equipment	5213	18.68
Interior Lighting	772	2.77
District Heating for Water	97	0.35
Performance Metrics	*(kWh/m²/year)*	
Total Site Energy	124	
Energy Per Conditioned Area	128	

However, the energy analysis of the Passivhaus model, in Table 6.16, reveals that cooling remains the dominant load, accounting for over 78% of the total site energy. Despite the significant thermal performance improvements, this demonstrates that mechanical cooling remains the primary energy demand in this climate. Interior equipment accounts for the second-largest share at almost 19%, while the contributions from lighting and domestic hot water are negligible. As the data reveals, the total site energy is about 28,000 kWh annually; considering the treated floor area (TFA), this translates to an annual electricity consumption of only 128 kWh/m²/a.

To evaluate the standard's adaptability, the investigation was extended to the four other climate zones. The results demonstrate the standard's versatility, although the extent of the energy savings was found to be highly dependent on the specific climatic challenges of each city. The following sections detail the energy performance comparison for each location.

6.3.2 Riyadh city (Zone Two)

In Riyadh's hot, arid climate, the PH model achieved a significant efficiency improvement. As detailed in Table 6.17, the Total Site Energy demand fell from 132.68 kWh/m²a to 111.02 kWh/m²a, about 21% reduction. This demonstrates the standard's effectiveness in an environment with high diurnal temperature variations.

Table 6.17. Simulated Energy Performance: Riyadh Baseline and Passivhaus Model

Energy Category	Base Model	PH Model	Reduction (%)
Total Site Energy (kWh)	31794.51	25,035.97	21.26
Total Site Energy (kWh/m²/year)	132.68	111.02	16.32
Energy for Cooling (kWh)	24993.63	18,893.52	24.41
Energy for Interior Equipment (kWh)	5672.39	5,213.11	8.10
Energy for Interior Lighting (kWh)	1030.87	771.68	25.14
District Heating for Space Heating (kWh)	0.00	60.26	N/A
District Heating for Water Systems (kWh)	97.62	97.4	0.23
Energy Per Conditioned Area (kWh/m²/year)	140.06	110.49	21.11

* Baseline space heating demand was zero; percentage change is undefined.

Implementing the Passivhaus standard in Riyadh yielded a profound reduction in energy consumption. The most notable result was the almost 25% decrease in energy for cooling, from 24,994 kWh/a to 18,893 kWh/a. This substantial saving underscores the standard's effectiveness in mitigating the high solar gains characteristic of the region. Overall, the Total Site Energy per conditioned area was reduced by 21%, demonstrating a comprehensive improvement in building performance. An interesting outcome of the highly insulated envelope was the emergence of a minor space heating demand of about 60 kWh/a, where none existed previously. This is likely due to reduced passive solar gains during the cooler winter period, necessitating a minimal amount of active heating to maintain comfort. On the other hand, PH cooling constituted the primary energy demand (c. 75%), followed by interior equipment (c. 20%). This represents a proportional shift from the baseline model, where cooling accounted for a higher share (c. 79%), indicating that improving the building envelope's thermal performance elevates the relative impact of unregulated internal loads on total energy consumption.

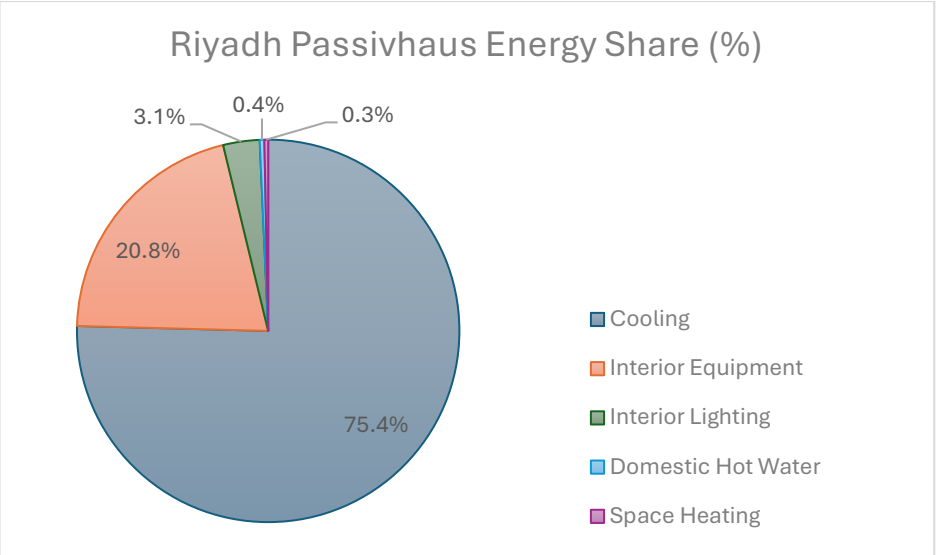


Figure 6.1. PH Performance in Riyadh

6.3.3 Dammam city (Zone Three)

In the hot and humid coastal climate of Dammam, the Passivhaus model also demonstrated considerable energy savings, as detailed in Table 6.18. The Passivhaus model illustrates only a 105 kWh/m² annually for the Energy Per Conditioned Area.

Table 6.18. Dammam Case Study

Energy Category	Base Model	PH Model	Reduction (%)
Total Site Energy (kWh)	31920.39	24,000.36	24.81
Total Site Energy (kWh/m²/year)	133.20	106.43	20.10
Energy for Cooling (kWh)	25119.50	17,880.62	28.82
Energy for Interior Equipment (kWh)	5672.39	5,213.11	8.10
Energy for Interior Lighting (kWh)	1030.87	771.68	25.14
District Heating for Space Heating (kWh)	0.00	37.55	N/A
District Heating for Water Systems (kWh)	97.62	97.4	0.23
Energy Per Conditioned Area (kWh/m²/year)	140.76	104.58	25.70

* Baseline space heating demand was zero; percentage change is undefined.

The results presented in Table 6.18 indicate a decrease in Total Site Energy from 133.20 kWh/m²a to 106 kWh/m²a. This 20% reduction is particularly noteworthy given the challenges of dehumidification and latent cooling loads associated with high humidity. The application of the PH in Dammam resulted in a significant performance improvement. The energy required for cooling was reduced from 25,120 kWh/a to 17,881 kWh/a. This led to a 29% reduction in the total cooling energy for the Treated Floor Area (TFA). Figure 6.2 provides further insight for the energy consumption of

PH. Cooling remains the dominant load, accounting for 74.5% of total consumption, with interior equipment making up the second-largest share with 21.7%. The results confirm the benefits of an airtight building envelope and mechanical ventilation in managing both sensible and latent heat gains.

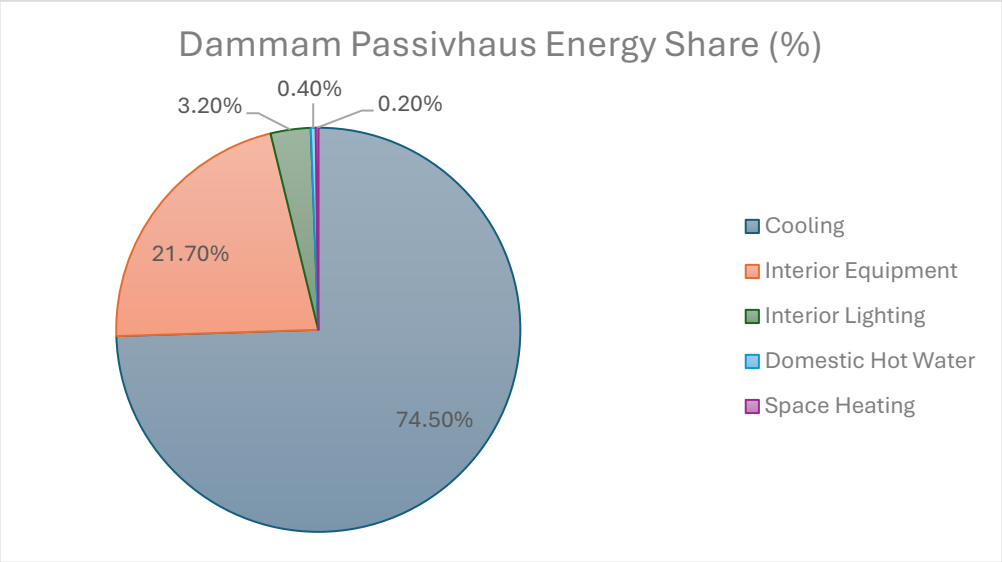


Figure 6.2 PH Performance in Dammam

6.3.4 Tabuk city (Zone Four)

For Tabuk, which experiences both hot summers and cooler winters, the Passivhaus proved highly effective. The detailed simulation results are presented in Table 6.19.

Table 6.19. Zone Four Represented City

Energy Category	Base Model	PH Model	Reduction (%)
Total Site Energy (kWh)	23,842.79	16,557	31
Total Site Energy (kWh/m²/year)	99.49	69	31
Energy for Cooling (kWh)	17,041.91	9,811	42
Energy for Interior Equipment (kWh)	5,672.39	5,213	8
Energy for Interior Lighting (kWh)	1,030.87	772	25
District Heating for Space Heating (kWh)	0.00	664	N/A
District Heating for Water Systems (kWh)	97.62	97	0.23
Energy Per Conditioned Area (kWh/m²/year)	95.50	55	42

* Baseline space heating demand was zero; percentage change is undefined.

The Passivhaus model achieved a substantial 31% reduction in total site energy intensity and a 42% decrease in cooling demand. This demonstrates the standard's year-round benefit, as the fabric-first principles that mitigate summer heat gain also

prevent winter heat loss. A key finding was the emergence of a 664 kWh/a space heating demand in the Passivhaus model, a direct consequence of the high-performance envelope reducing passive solar gains during colder months. The resulting energy profile, illustrated in Figure 6.3, is more balanced than in the other cities; while cooling is the largest load (59.3%), both interior equipment (31.5%) and space heating (4.0%) represent significant shares of consumption. This outcome highlights the standard's suitability for mixed climates but also underscores the necessity of including an efficient heating system in such designs.

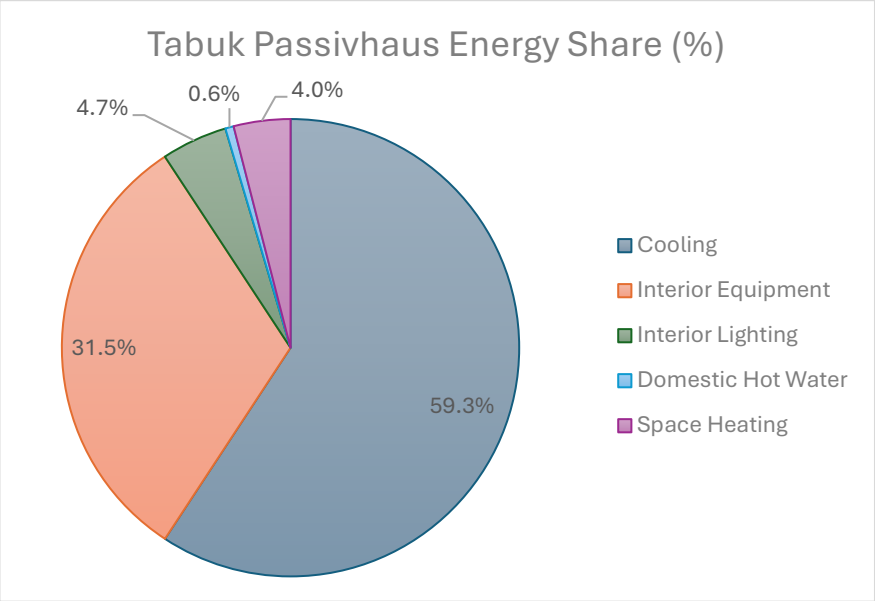


Figure 6.3 PH Performance in Tabuk

6.3.5 Abha city (Zone Five)

The most substantial performance improvement was observed in the mild, high-altitude climate of Abha. The detailed simulation results are presented in Table 6.20.

Table 6.20. Simulated Models for Abha City

Energy Category	Base Model	PH Model	Reduction (%)
Total Site Energy (kWh)	25754.19	8123.06	68.46
Total Site Energy (kWh/m²/year)	107.47	36.02	66.48
Energy for Cooling (kWh)	18953.31	1972.95	89.59
Energy for Interior Equipment (kWh)	5672.39	5213.11	8.10
Energy for Interior Lighting (kWh)	1030.87	771.68	25.14
District Heating for Space Heating (kWh)	0.00	67.92	N/A
District Heating for Water Systems (kWh)	97.62	97.4	0.23
Energy Per Conditioned Area (kWh/m²/year)	106.21	11.54	89.14

* Baseline space heating demand was zero; percentage change is undefined.

The Passivhaus standard demonstrated exceptional efficacy in Abha's temperate climate, yielding the most significant energy savings of the five cities. The total site energy intensity was reduced by a remarkable 66.5%, from 107.47 kWh/m²a to just 36.02 kWh/m²a. This was driven by a near-elimination of the cooling demand, which fell by almost 90%, as in Table 6.20. The energy breakdown for the Passivhaus model, illustrated in Figure 6.4, reveals a dramatic shift in the building's energy profile. With cooling reduced to only 24.29% of the total consumption, the unregulated internal load from interior equipment becomes the dominant factor, accounting for over 64% of the site energy. This finding is critical, as it highlights that in highly optimised, fabric-first buildings in mild climates, managing and reducing internal gains becomes the primary strategy for achieving further energy savings.

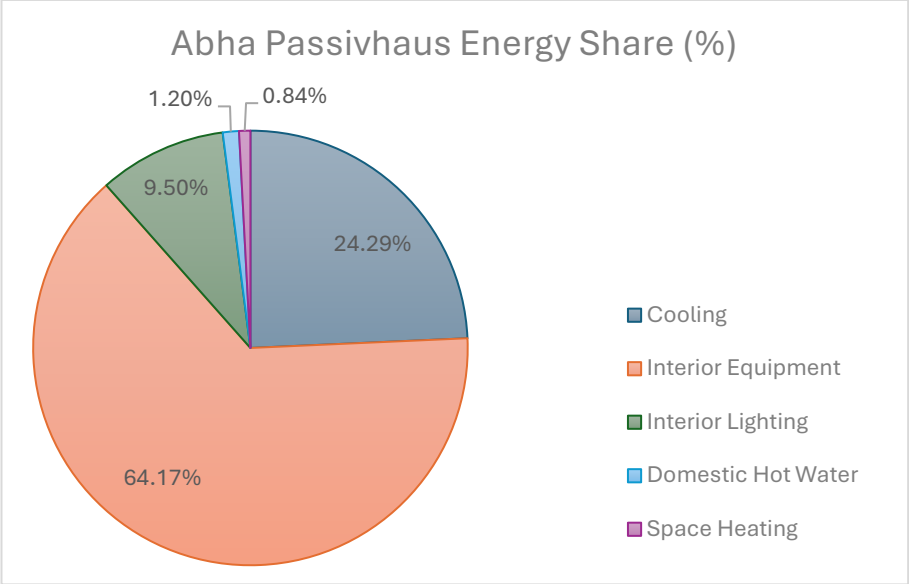


Figure 6.4. PH Energy Performance in Abha

The analysis across all five climatic zones demonstrates the Passivhaus standard's remarkable adaptability to Saudi Arabia's diverse environmental conditions. While energy savings ranged from 21% in Dammam's humid coastal climate to an exceptional 66% in Abha's mild high-altitude environment, the consistent theme across all locations was the fabric-first approach's effectiveness in substantially reducing cooling demand—the dominant energy load in Saudi residential buildings. These results establish Passivhaus as a viable, high-performance benchmark that significantly exceeds SBC requirements, providing a robust foundation for the comparative analysis presented in Section 6.4.

6.4 Summary

The primary investigation began with the improved baseline model located in Madinah upgraded to the Saudi Building Code, followed by an expanded analysis applying the standard to the baseline models in four other cities, each representing a distinct climate zone within Saudi Arabia. The objective was to quantify the performance improvements, highlight key findings from the simulations, and draw comparisons between the baseline, the SBC, and finally the Passivhaus-retrofitted models in each city.

The simulation results provide strong evidence for the efficacy and versatility of the Passivhaus standard across all five Saudi climate zones. The application of PH principles yielded energy demand reductions ranging from 21.26% in Riyadh to 68.46% in Abha. The 'fabric-first' methodology was the most critical factor in mitigating thermal gains and losses. These findings indicate that the Passivhaus standard, originally developed for cold climates, offers a potent and adaptable framework for creating ultra-low-energy buildings in the varied climates of Saudi Arabia.

Table 6.21 Comparison of Total Site Energy Savings between the SBC and Passivhaus Standards Across Five Saudi Cities

City	SBC Savings (%)	Passivhaus Savings (%)	Passivhaus Improvement over SBC (%)
Madinah	15.84	24.61	10.43
Riyadh	16.12	21.26	6.13
Dammam	17.52	24.81	8.84
Tabuk	18.42	30.56	14.88
Abha	36.75	68.46	50.13

To consolidate these findings, Table 6.21 compares the total site energy savings achieved by the SBC and Passivhaus standards across the five cities. The data illustrate that while the SBC guarantees baseline energy reductions, ranging from 15.84% in Madinah to 36.75% in Abha, the Passivhaus standard consistently outperforms it across every climate zone. Most notably, the Passivhaus application in Abha yields an exceptional 68.46% overall reduction, demonstrating the largest margin of improvement (50.13%) over the SBC. Even in the more challenging climates of Riyadh and Dammam, Passivhaus secures significant additional efficiencies, validating its adaptability as a robust standard for ultra-low-energy building design in Saudi Arabia.

7 RESULTS AND DISCUSSION

7.1 Introduction

Following the detailed application and simulation of the Saudi Building Code (SBC) and the Passivhaus (PH) standard in Chapter 6, this chapter transitions from the presentation of technical data to a comprehensive discussion of its broader implications. The preceding analysis quantified the energy performance of residential buildings under these distinct standards. This chapter now synthesises these findings to build a compelling case for the adoption of a new, high-performance building approach in The Kingdom of Saudi Arabia.

The primary purpose of this chapter is to analyse the strategic importance of the simulation results within the context of national policy, established construction practices, and the climate-specific challenges of the region. The discussion is structured to first provide a holistic overview of the findings, then evaluate the efficacy of the current Saudi Building Code and finally contrast this with the transformative potential demonstrated by the Passivhaus standard. By defining and analysing the critical performance gap between these standards, this chapter establishes a clear rationale for the specific adaptation strategies that are to be investigated in Chapter 8.

Figure 7.1 illustrates three simulation modelling outcomes for energy consumption in the case study conducted in Madinah, which include the base Model, the Saudi Building Code model, and the Passivhaus model. These outcomes include validation, the implementation of SBC, and an enhancement to the Passivhaus standard. The data displays each model's energy consumption, measured in kilowatt-hours (kWh), and the percentage reduction for SBC and Passivhaus.

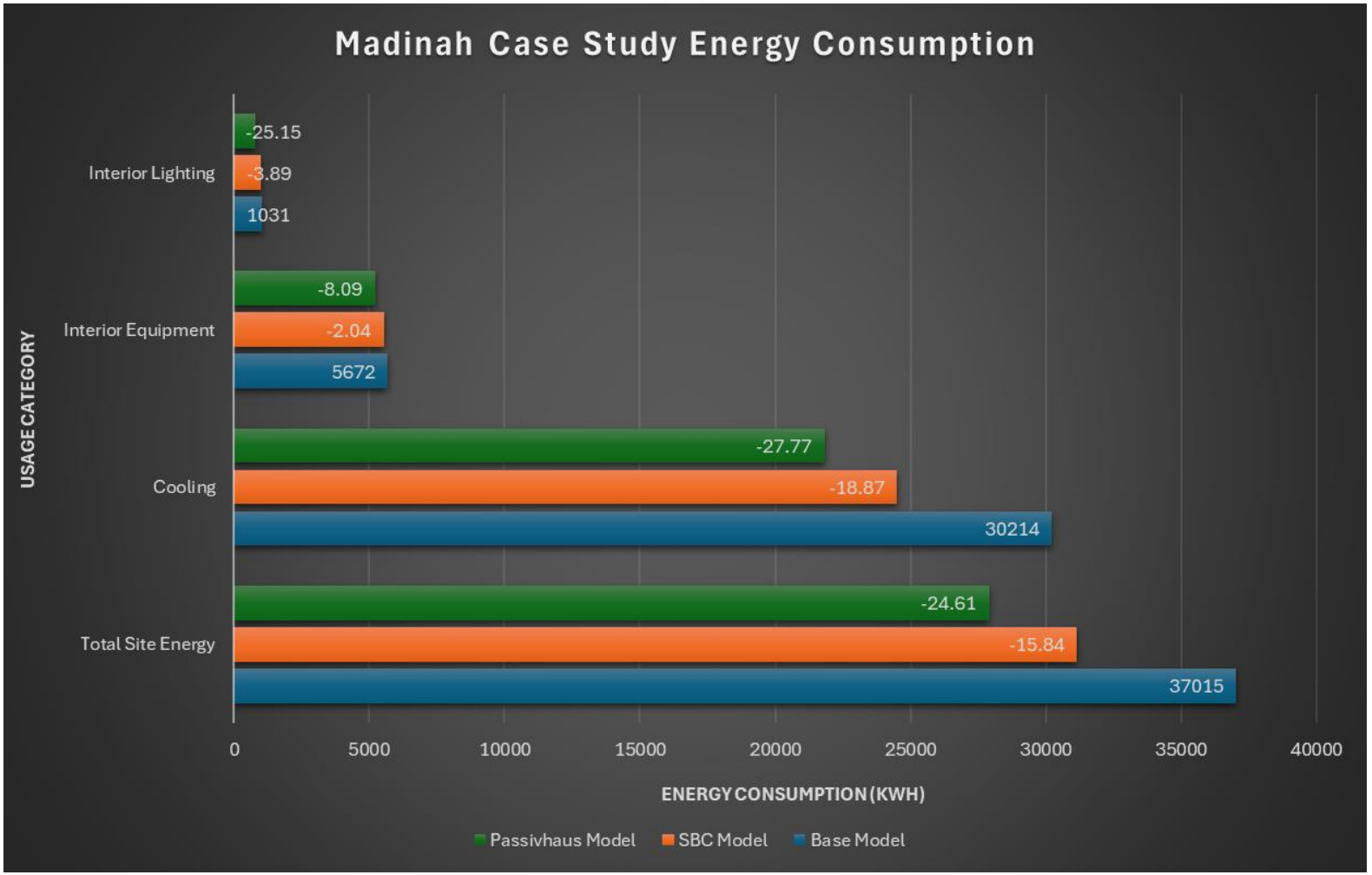


Figure 7.1. Comparing Baseline Model, SBC, and PH in Madinah

The base case study has a usage of 37,015 kWh, the SBC model has a usage of 31,153 kWh, and the Passivhaus model has a usage of 27,905 kWh. Applying the Passivhaus standard to the base model results in a significant energy savings of 9,110 kWh, or a nearly 25% reduction. In contrast, the SBC approach provides a savings of merely 16%.

For the cooling demand, as illustrated in Figure 7.1, the Passivhaus shows a decrease in electricity consumption of 27.77%, while the SBC reduces it by 18.87%. This high energy demand is primarily due to the hot climate and the lack of energy-efficient building practices. The findings of this study underscore the significant impact that building standards and energy-efficient designs can have on reducing energy consumption in residential buildings. Indeed, the Passivhaus is a remarkable example of an energy-efficient code that significantly benefits the Saudi residential sector by reducing power use.

7.2 Performance Analysis

This section presents the comprehensive energy performance results from all simulations, providing the foundational evidence for the subsequent discussion. The analysis begins with a holistic overview before examining the performance of each standard individually. Figure 7.2 illustrates the total site energy and the energy for cooling for the Baseline models, the SBC models, and the Passivhaus (PH) models across all the five selected case study cities.

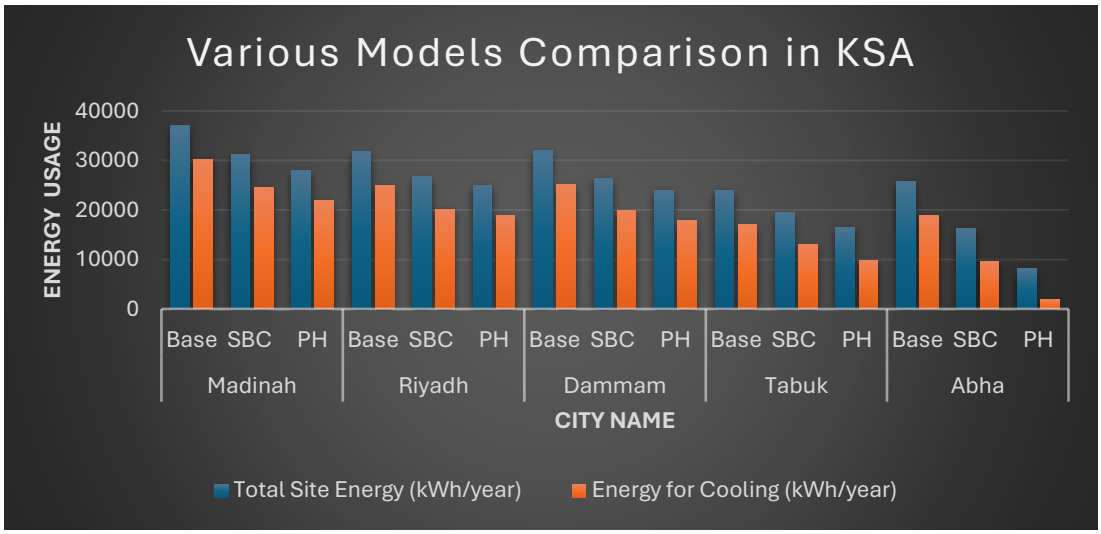


Figure 7.2. Different Standards Comparison Across Saudi Arabia

The data reveals several key findings that will be explored in this chapter. Firstly, a consistent, stepwise reduction in energy consumption is evident as the models' progress from the baseline to the SBC and subsequently to the Passivhaus standard. Secondly, it visually confirms that energy for cooling is the predominant component of the total site energy in nearly all cases, and thus the primary driver of savings. Finally, the chart highlights the unique performance characteristics of Abha, where baseline energy consumption is lower and the reductions achieved are visibly more pronounced. This summary provides the visual foundation for the detailed analysis that follows.

The findings from the application of the Saudi Building Code (SBC) mark a crucial first step in the Kingdom's journey towards energy efficiency. As demonstrated by the simulation results detailed in Chapter 6, the implementation of the SBC consistently yields significant energy savings when compared to the baseline model. Figure 7.3 demonstrates the percentage reduction in total energy, highlighting the code's impact.

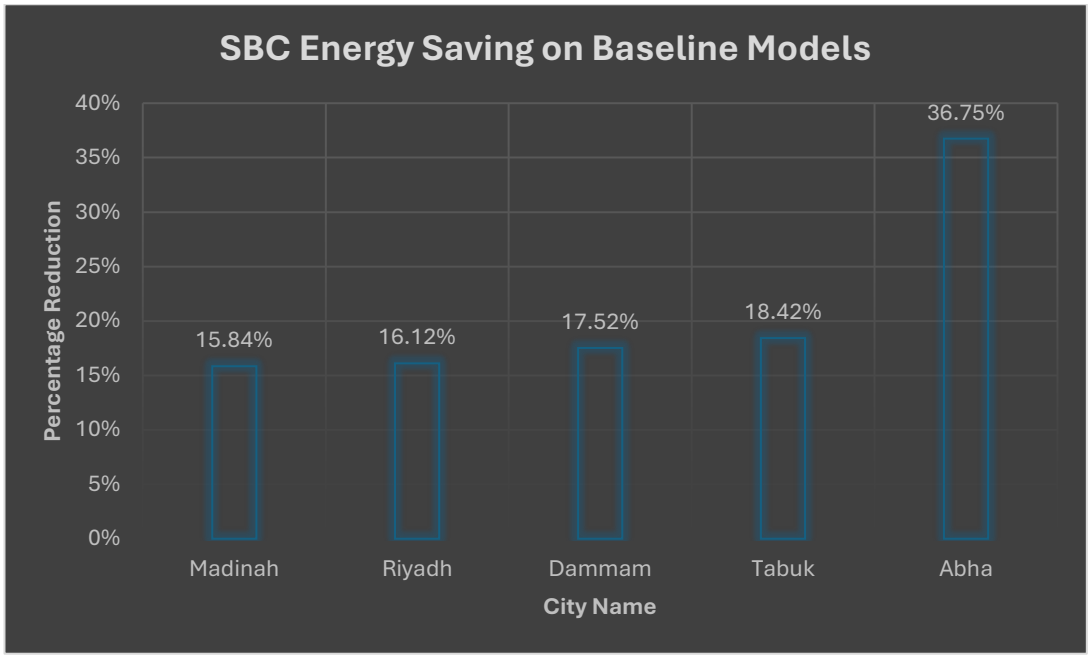


Figure 7.3. Total Site Energy Saving for SBC vs. Baseline Across Five Saudi Cities

The reduction in total site energy consumption ranged from nearly 16% in Madinah to 18.4% in Tabuk, establishing the code as an effective tool for curbing energy demand. However, the analysis reveals a critical nuance: the code's effectiveness is highly dependent on the regional climate. The city of Abha, with its unique high-altitude climate, emerged as a significant outlier with a dramatic 36.7% reduction in total site energy. This disparity suggests that while the SBC provides a robust foundational improvement, its prescriptive measures are exceptionally well-suited to milder climates, potentially offering diminishing returns in the harsher climates that characterise much of the Kingdom. Ultimately, the SBC serves as an essential regulatory instrument, but the variance in its impact indicates it represents a conservative step rather than a transformative one.

While the SBC establishes an improved baseline, applying the Passivhaus standard reveals the true scale of what is technically achievable. The results from the Passivhaus models represent not merely an incremental improvement, but a paradigm shift, establishing a new and ambitious performance benchmark for both energy efficiency and occupant comfort.

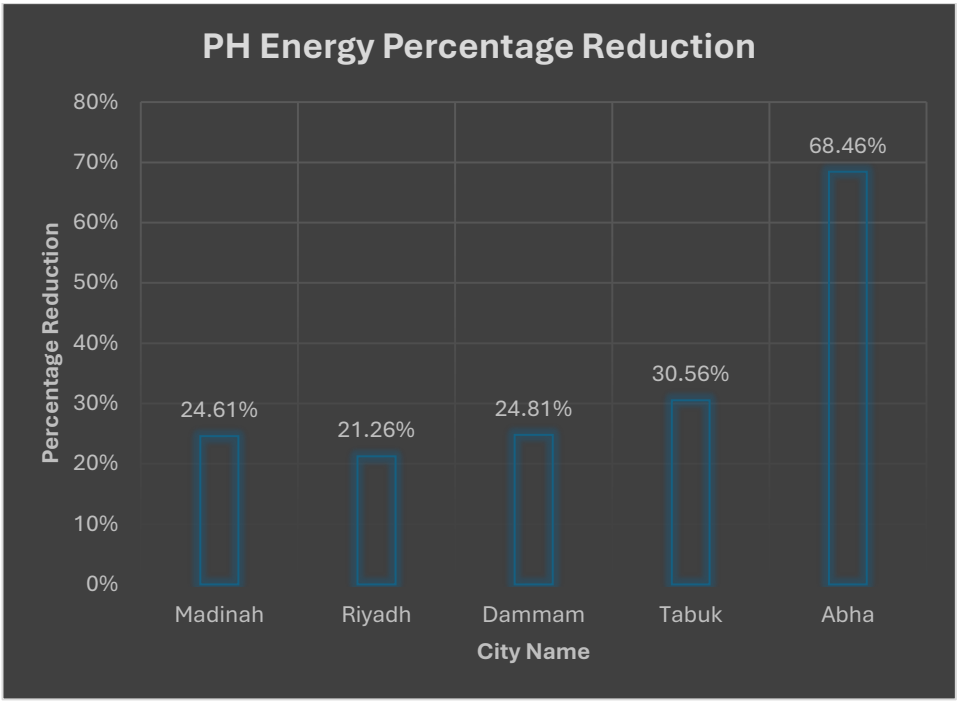


Figure 7.4. Total Site Energy Saving for PH vs. Baseline Across Five Saudi Cities

As synthesised in Figure 7.4, the Passivhaus models deliver a transformative reduction in total site energy, with savings ranging from 21% in Riyadh to an exceptional 68.5% in Abha. Beyond the energy savings, the standard delivered a profound improvement in indoor environmental quality. As detailed in Appendix D, the Passivhaus models not only eliminated all unmet cooling hours but also drastically reduced ASHRAE 55 discomfort hours. This demonstrates that the standard's holistic approach provides a dual benefit: it radically reduces the operational energy footprint while simultaneously creating a far more stable, comfortable, and resilient indoor environment for occupants. The Passivhaus simulations, therefore, prove that an international best-practice standard can unlock a far deeper level of performance, confirming that ultra-low energy, high-comfort buildings are a technically viable objective across the diverse climatic zones of Saudi Arabia.

7.3 Interpretation and discussion

The crucial analysis lies in the direct comparison between the SBC and Passivhaus standard, which reveals a substantial 'performance gap' between current national regulations and international best practice. This gap represents the untapped potential for energy savings and carries profound implications for the future of the built environment in the Kingdom. The critical insight comes from analysing the additional energy savings achieved when applying Passivhaus principles directly to the improved SBC models, as illustrated in Figure 7.5

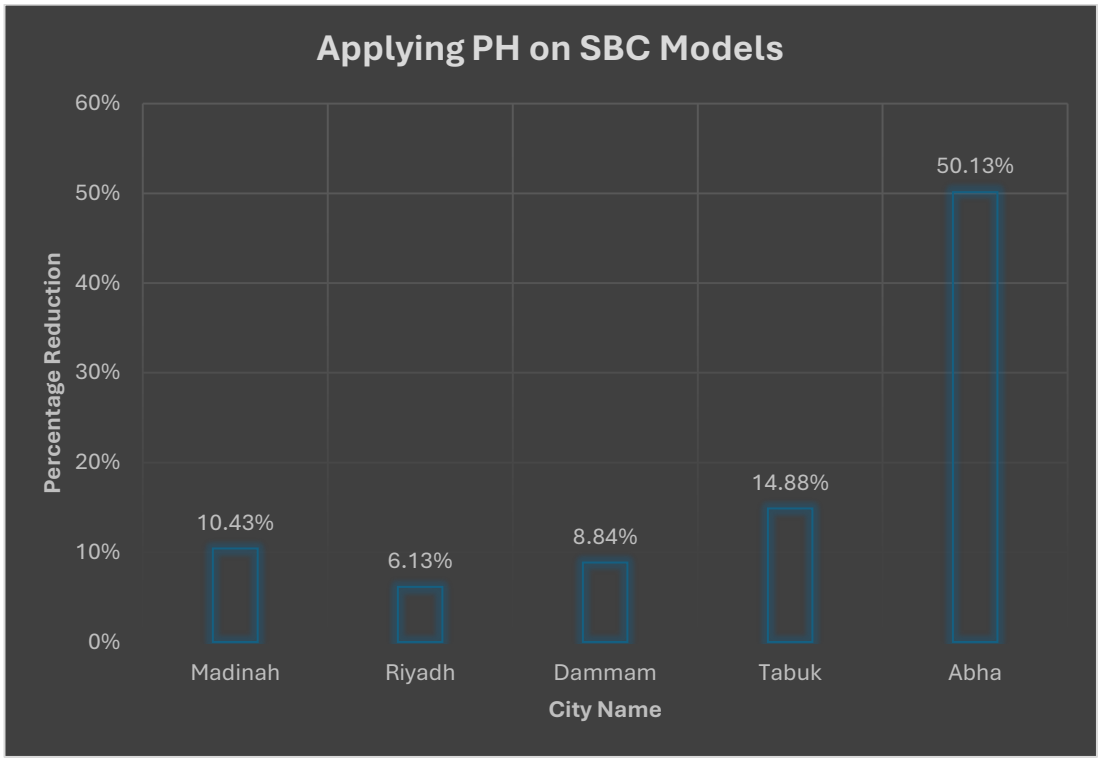


Figure 7.5 Total Site Energy Saving for PH on SBC Models Across Five Saudi Cities

This demonstrates the true scale of the performance gap: the untapped energy-saving potential that exists beyond the current national standard. In addition, the data illustrates that a further 6% to 15% energy reduction is achievable in the climates represented by Zones 1, 2, 3, and 4. On the other hand, in climatic Zone 5 (Abha), the Passivhaus standard unlocks a remarkable 50% in energy savings over and above the SBC's already notable improvements. This proves that while the SBC is a vital step forward, it leaves substantial potential energy savings unachieved.

This identified performance gap provides a clear, evidence-based argument for the future evolution of the Saudi Building Code. Currently, the SBC serves its purpose as a crucial regulatory tool that establishes a baseline of minimum performance. However, the findings of this research demonstrate that there is a substantial opportunity to raise this bar considerably. By providing a quantified benchmark of what is achievable, this study offers a roadmap for future iterations of the SBC, guiding it from a framework of minimum compliance towards one that encourages or even mandates a much higher tier of building performance. The demonstration of this performance gap creates a clear strategic imperative: to determine how high performance can be pragmatically and effectively implemented. This necessitates a detailed investigation into adapting the principles of the Passivhaus standard to the specific climatic conditions and construction practices in Saudi Arabia, the challenge that the subsequent chapter will address.

Figure 7.6 demonstrates the superior energy savings of Passivhaus (PH) over SBC for the base model across five cities. PH consistently outperforms SBC, with the greatest potential evident in Abha's cooler climate, highlighting its adaptability to diverse Saudi conditions.

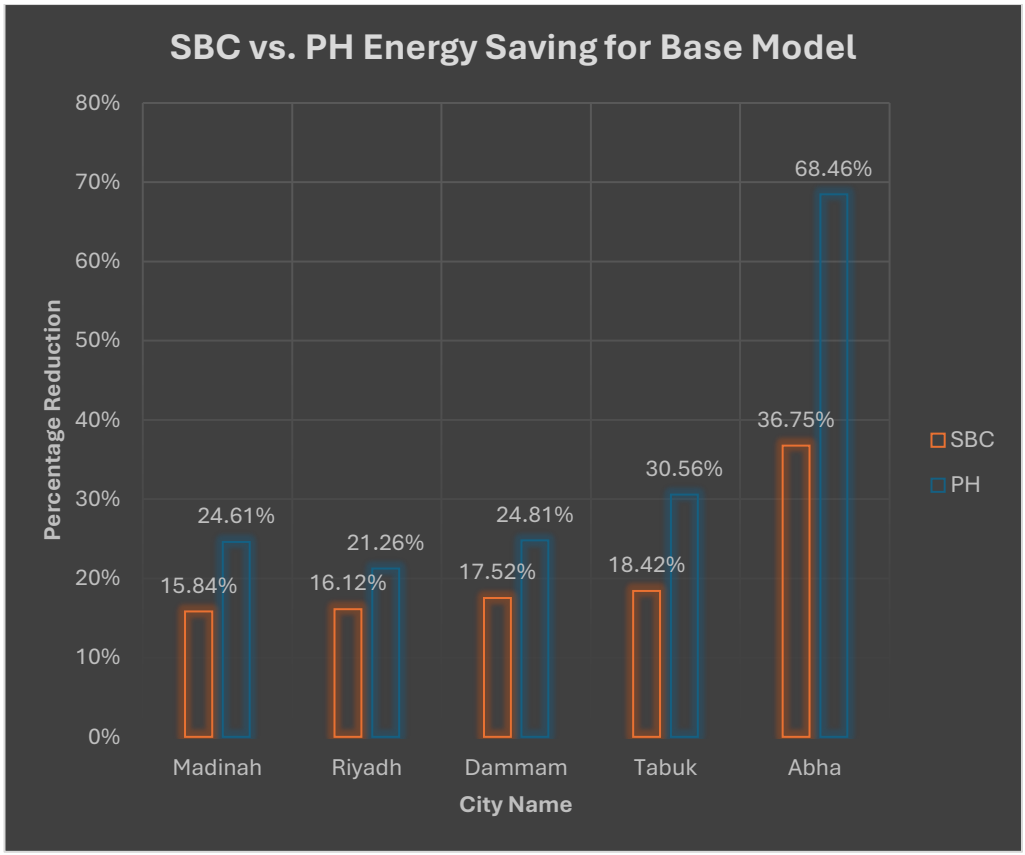


Figure 7.6. Comparing SBC and PH on the Baseline Models

7.4 Limitations of the Baseline Model

In interpreting the results presented in this chapter, it is necessary to acknowledge the methodological boundaries associated with the reliance on a single residential typology and fixed occupancy profiles. The baseline model utilised throughout this analysis was strictly defined as a typical Saudi residential flat located within a two-storey building, initially contextualised for Madinah. This singular geometric model was subsequently applied across the remaining four Saudi climate zones. Similarly, the study adopted a fixed occupancy assumption, simulating a standard Saudi family of five members adhering to a static daily schedule derived from established academic literature.

The primary rationale for fixing these parameters was the methodological necessity of establishing a rigorously controlled baseline. By maintaining a constant building form and operational schedule across all five climate zones, this study successfully isolated the variable of interest: the specific impact of the Passivhaus standard and the Saudi Building Code (SBC) on building performance. Introducing regional variations in building typology or stochastic, highly variable occupancy profiles in each zone would have introduced significant confounding variables, thereby precluding a direct, fair, and rigorous comparative analysis of the energy and thermal standards.

However, it is important to transparently address the limitations this approach places on the generalisability of the absolute performance data. The Saudi residential sector comprises diverse architectural forms, such as a villa, which possess distinct surface-area-to-volume ratios and will subsequently interact differently with local microclimates. Furthermore, actual occupant behaviour is inherently dynamic. Deviations from the assumed family size or daily routine, such as varying working-from-home patterns, different cooling set-points, or irregular appliance usage, would inevitably alter the magnitude of internal heat gains and peak energy demand. Consequently, while the comparative trends and relative performance improvements between the SBC and Passivhaus standards remain robust across the climate zones, the absolute energy consumption figures should be understood as representative of this specific, controlled scenario rather than universally predictive of all Saudi residential buildings.

7.5 Summary

This chapter has provided a comprehensive discussion and synthesis of the energy performance findings first presented in Chapter 6. The analysis confirmed that the Saudi Building Code serves as an essential instrument, establishing a new baseline for energy efficiency. However, this research has demonstrated that the SBC's impact, while notable, is conservative when compared to the transformative potential of the international Passivhaus standard. The central argument of this chapter is the identification of a critical 'performance gap' between the national standard and what is technically achievable. This gap, quantified by substantial additional energy and comfort improvements, represents a major strategic opportunity to elevate the standard of the Kingdom's built environment. By proving that an ultra-low energy, high-comfort outcome is a viable objective, this chapter has established the evidence-based rationale for adopting a higher-performance building approach. The discussion now naturally progresses to the practical how. Having established the case for pursuing this higher standard, the subsequent chapter will address the crucial questions of implementation, validation, and optimisation.

8 ADAPTING PASSIVHAUS FOR SAUDI ARABIA

8.1 Introduction

The preceding chapter provided a comprehensive discussion of the energy performance results, establishing a clear 'performance gap' between the Saudi Building Code (SBC) and the Passivhaus standard (Passive House). The analysis concluded that while the SBC is a vital step, the Passivhaus standard represents a transformative, high-performance approach that is technically achievable, as demonstrated by the results in Abha. This chapter builds upon that finding to address the central research questions of feasibility and optimisation.

To do so, the analysis will first assess the feasibility of the Passivhaus models from Chapter 7, examining their performance against the official certification requirements to determine if they can be certified. Following this validation, the chapter will then investigate the optimisation of these models through a detailed analysis of the Window-to-Wall Ratio (WWR), seeking an optimal balance between energy performance and thermal comfort. The chapter will conclude with a discussion of the challenges and limitations inherent in applying the standard, followed by a summary of its findings.

8.2 Examining Passivhaus in the Saudi Climate

The first step in adapting the Passivhaus standard is to conduct a feasibility study, evaluating the performance of the simulated models from Chapter 7 against the stringent Passivhaus Classic certification criteria for new builds. This validation establishes a crucial baseline: is the standard, as applied, already achievable in any of the representative Saudi climates?

The main criteria for the Passivhaus Classic standard (for new builds) are:

- Heating Demand: ≤ 15 kWh/(m²a)
- Cooling Demand: ≤ 15 kWh/(m²a)
- Airtightness (n_{50}): ≤ 0.6 ach
- Total Energy Demand: ≤ 120 kWh/(m²a)
- Opaque Component U-values (Walls, Roof): ≤ 0.15 W/(m²K)
- Window U-value: ≤ 0.80 W/(m²K)

For this analysis, several methodological clarifications are necessary. The airtightness for all models was simulated at 0.6 Ach, meeting the criterion by design. The component U-values were defined as inputs in the simulation as detailed in Chapter 6. The validation in Table 8.1 focuses on the primary performance metrics. For the criterion of Total Energy Demand, this analysis will use the Total Site Energy (kWh/m²a) metric. This value, which represents the total energy consumed at the building boundary for all uses (cooling, heating, hot water, and electricity), is directly compared against the ≤ 120 kWh/(m²a) limit. For the Cooling Demand, the Energy Per Conditioned Area (kWh/m²a) is used for the specific cooling demand metric.

Table 8.1. Passivhaus Feasibility in Saudi Climates

Climate Zone/PH Requirements	Heating Demand (kWh/m²a) ≤ 15	Cooling Demand (kWh/m²a) ≤ 15	Total Energy Demand (kWh/m²a) ≤ 120	Meets Passivhaus All Must Pass
Zone 1 (Madinah)	0.00 (Pass)	128.00 (Fail)	124.00 (Fail)	Fail
Zone 2 (Riyadh)	3.18 (Pass)	110.49 (Fail)	111.02 (Pass)	Fail
Zone 3 (Dammam)	0.22 (Pass)	104.58 (Fail)	106.43 (Pass)	Fail
Zone 4 (Tabuk)	3.89 (Pass)	55.00 (Fail)	69.00 (Pass)	Fail
Zone 5 (Abha)	0.40 (Pass)	11.54 (Pass)	36.02 (Pass)	Pass

The results from this feasibility study are unambiguous. For four of the five selected cities, the PH model fails to meet the Passivhaus Classic criteria. The primary cause for failure in all cases is the Cooling Demand, which ranges between 55 and 128 kWh/m²a, dramatically exceeds the stringent ≤ 15 kWh/m²a limit. This finding is central to the thesis, as it confirms that a direct application of the standard is not feasible for most of Saudi Arabia. Indeed, the zones are 1,2,3, and 4.

However, the model for Zone 5, Abha city, emerges as a major success, passing all three criteria. This proves that in the Kingdom's zone five climates, the Passivhaus standard is not only viable but a highly effective and achievable benchmark.

8.3 Optimising Performance for the Saudi Climate

Since the Passivhaus standard does not mandate a specific requirement for the window-to-wall ratio, this study examined various WWR options and their impact on energy consumption and thermal comfort. Meanwhile, the feasibility analysis has highlighted that whilst the building envelope specifications, such as insulation and airtightness, are robust, they remain insufficient to independently manage cooling loads in Saudi Arabia's hotter climate zones. This limitation necessitates a strategic shift from validation to optimisation. Therefore, this section investigates how the building design can be specifically adapted to enhance performance, prioritising the Window-to-Wall Ratio (WWR) as the critical parameter for controlling solar gain and balancing energy efficiency with thermal comfort. In other words, the results will seek a better optimisation for adapting the PH standard in the Kingdom of Saudi Arabia.

8.3.1 Optimising Building Energy Performance by WWR

This research initiates by examining the main case study, Madinah, following by toe remaining zones representing Saudi Arabia.

Zone One Optimisation, Madinah City

Table 8.2 illustrates the comprehensive energy efficiency and thermal comfort results in Madinah based on the Window-to-Wall Ratio (WWR), ranging from 5% to 20%. The WWR values increase in increments of 5%, with additional intermediate values of 8% and 12% included for a more detailed illustration. The parametric data presented in the table highlights several critical aspects of building performance in the hot-dry climate of Saudi Arabia, recommended Zone 1.

A primary observation is the stability of the indoor thermal environment; across all WWR configurations, the Average Operative Temperature remains notably consistent and favourable, fluctuating only slightly between 24.26°C and 24.40°C. This indicates that all tested variations maintain an average temperature below 25°C, suggesting a baseline level of thermal control regardless of aperture size.

Regarding energy performance, the data reveals a direct correlation between increased window area and higher energy demand. As the WWR increases, the total energy consumption rises accordingly. Specifically, increasing the WWR from the lowest tested ratio of 5% to the highest of 20% results in a Total Site Energy increase from 112.98 kWh/m²a to 120.64 kWh/m²a. This represents a percentage increase of approximately 6.78% in total energy consumption.

Table 8.2 Madinah PH Model Performance with Various WWR

No	Parameter	5%	8%	10%	12%	15%	20%
1	Total Site Energy (kWh)	25,608.68	25,978.20	26,213.06	26,443.59	26,827.52	27,345.98
2	Total Site Energy (kWh/m²/year)	112.98	114.61	115.64	116.66	118.35	120.64
3	Energy for Cooling (kWh)	19,544.84	19,914.37	20,149.22	20,379.76	20,719.50	21,282.15
4	Energy for Interior Equipment (kWh)	5,190.61	5,190.61	5,190.61	5,190.61	5,190.61	5,190.61
5	Energy for Interior Lighting (kWh)	775.65	775.65	775.65	775.65	775.65	775.65
6	Energy for District Heating/Hot Water (kWh)	97.58	97.58	97.58	97.58	97.58	97.58
7	Energy per Conditioned Area (Cooling only)	114.3	116.46	117.83	119.16	121.17	124.46
8	Unmet Cooling Hours	1,303.00	1,323.25	1,332.75	1,337.50	1,341.25	1,348.25
9	ASHRAE 55 Discomfort Hours	1,959.50	1,957.00	1,953.25	1,950.50	1,946.50	1,949.50
10	Average Operative Temperature (°C)	24.31	24.33	24.26	24.27	24.32	24.40

This rise in energy use is driven predominantly by the cooling load. Across all scenarios, cooling energy remains the dominant consumer, accounting for approximately 76% to 78% of the total site energy. Furthermore, in terms of occupant comfort, the ASHRAE 55 Discomfort Hours remain relatively high but stable across the dataset, with a mean value of approximately 1,953 hours for the tested range. These findings quantify the significant impact of solar gain through glazing on the building's energy profile while underscoring the persistent challenge of maintaining thermal comfort in this climate zone.

To find the optimal balance between the energy consumption and the thermal comfort, three parameters chosen for each category to be normalised. For the energy usage, the parameters are Total Site Energy (kWh), Energy for Cooling (kWh), and Energy per Conditioned Area (Cooling only). While for the thermal comfort, the main aspects are Avg. Operative Temp (°C), Unmet Cooling Hours, and the Discomfort Hours (ASHRAE 55).

Zone Two Optimisation, Riyadh City

Following the analysis of Madinah, the study extends to Riyadh, representing Climate Zone 2. This zone is characterised by extreme aridity and high solar radiation, presenting a distinct set of challenges for building optimization. The simulation focused on a range of Window-to-Wall Ratios (WWR) from 5% to 20% to identify the most effective balance between minimizing cooling loads and maintaining occupant comfort.

The results for Riyadh demonstrate a consistent relationship between window area and energy consumption, mirroring the trends observed in Zone 1. As detailed in Table 8.3, the model achieves its lowest energy footprint at the 5% WWR configuration. As the WWR increases to 20%, the Total Site Energy rises, driven directly by the increased solar heat gain which places a higher demand on the cooling system.

Moreover, the Total Site Energy increases from 101.47 kWh/m²a at 5% WWR to 107.86 kWh/m²a at 20% WWR. This represents a percentage increase of approximately 6.3% across the tested range. The Energy for Cooling remains the single largest component of the energy balance, increasing from 16,875 kWh at 5% WWR to 18,346 kWh at 20% WWR.

In terms of thermal comfort, the analysis of ASHRAE 55 Discomfort Hours provides critical insight into the liveability of the space. The data indicates that as the WWR increases, the number of discomfort hours decreases, suggesting that for this specific model configuration in Riyadh, larger windows (up to 20%) may be beneficial for comfort, possibly due to daylighting or passive solar gains during cooler periods. The lowest number of discomfort hours (2,851 hours) is achieved at the highest tested WWR of 20%. The Average Operative Temperature remains stable across all options, fluctuating slightly between 23.39°C and 23.52°C.

Table 8.3 Riyadh Passivhaus Model Performance with Various WWR

No	Parameter	5%	8%	10%	12%	15%	20%
1	Total Site Energy (kWh)	23001.02	23311.61	23507.43	23698.81	23981.26	24448.11
2	Total Site Energy (kWh/m²/year)	101.47	102.84	103.71	104.55	105.8	107.86
3	Energy for Cooling (kWh)	16875.47	17192.63	17392.07	17392.11	17873.67	18346.9
4	Energy for Interior Equipment (kWh)	5190.61	5190.61	5190.61	5190.61	5190.61	5190.61
5	Energy for Interior Lighting (kWh)	775.65	775.65	775.65	775.65	775.65	775.65
6	Energy for District Heating/Hot Water (kWh)	97.58	97.58	97.58	97.58	97.58	97.58
7	Energy per Conditioned Area (Cooling only)	99.85	100.52	101.12	102.85	104.53	107.01
8	Unmet Cooling Hours	1113	1134.75	1139	1146.75	1154.75	1166.5
9	ASHRAE 55 Discomfort Hours	2946	2924.5	2910	2897.75	2876	2851
10	Average Operative Temperature (°C)	23.39	23.42	23.44	23.45	23.48	23.52

Zone Three Optimisation, Dammam City

The analysis proceeds to Dammam, representing Climate Zone 3. Situated on the Arabian Gulf coast, Dammam experiences a hot-humid climate distinct from the arid interior, where high humidity levels significantly influence latent cooling loads and thermal comfort perception. The optimization study examined the same WWR range of 5% to 20%.

The simulation results for Dammam reveal a linear correlation between the extent of glazing and overall energy demand, consistent with the patterns in other zones but influenced by the coastal climate. As presented in Table 8.4, the minimal energy footprint is observed at the 5% WWR. Increasing the window area to 20% results in a corresponding rise in Total Site Energy, driven by the combined impact of solar gain and the specific cooling requirements of a humid environment.

Quantitatively, the Total Site Energy escalates from 95.26 kWh/m²a at 5% WWR to 101.64 kWh/m²a at 20% WWR. This constitutes a percentage increase of approximately 6.7% across the analysed range. The Energy for Cooling remains the dominant factor, rising from 15,396 kWh to 16,848 kWh, underscoring the penalty of increased solar aperture on the active cooling systems.

The thermal comfort assessment, based on ASHRAE 55 Discomfort Hours, indicates a favourable trend associated with larger window areas in this specific context. Like Riyadh, the number of discomfort hours decreases as the WWR increases. This suggests that a more generous glazing ratio (up to 20%) contributes positively to the indoor environmental quality, potentially by balancing internal loads or facilitating heat dissipation during specific periods. The minimum number of discomfort hours (4,372 hours) coincides with the highest tested WWR of 20%. The Average Operative Temperature shows a slight upward trend but remains well-controlled, ranging from 24.96°C to 25.12°C.

Indeed, the optimization for Dammam presents a clear divergence between energy conservation and occupant comfort goals. While the 5% WWR is the most energy-efficient strategy, the 20% WWR yields the superior thermal comfort outcome. A 10% WWR is selected as the balanced design strategy, weighing the marginal energy penalty of larger windows against tangible improvements in habitability.

Table 8.4 Dammam Passivhaus Model Performance with Various WWR

No	Parameter	5%	8%	10%	12%	15%	20%
1	Total Site Energy (kWh)	21,447.90	21,761.20	21,955.38	22,141.79	22,415.27	22,883.30
2	Total Site Energy (kWh/m²/year)	95.26	96.66	97.52	98.35	99.56	101.64
3	Energy for Cooling (kWh)	15,395.74	15,713.46	15,910.21	16,098.93	16,375.64	16,848.14
4	Energy for Interior Equipment (kWh)	5,135.13	5,135.13	5,135.13	5,135.13	5,135.13	5,135.13
5	Energy for Interior Lighting (kWh)	770.41	770.41	770.41	770.41	770.41	770.41
6	Energy for District Heating/Hot Water (kWh)	96.99	96.99	96.99	96.99	96.99	96.99
7	Energy per Conditioned Area (Cooling only)	90.03	91.89	93.04	94.15	95.76	98.53
8	Unmet Cooling Hours	721	720.25	723.5	725.75	724.25	713
9	ASHRAE 55 Discomfort Hours	4,544.25	4,512.75	4,485.50	4,466.50	4,424.50	4,372.25
10	Average Operative Temperature (°C)	24.96	25	25.02	25.04	25.07	25.12

Zone Four Optimisation, Tabuk City

The optimisation analysis continued with Tabuk, representing Climate Zone 4. Tabuk's climate, while arid, can experience colder winter temperatures than other regions, potentially influencing the interplay between solar gain, heating requirements, and cooling loads. The study applied the same WWR variations.

Consistent with the findings in other zones, the simulation results for Tabuk demonstrate a linear increase in energy consumption correlating with larger window areas. As detailed in Table 8.5, the model achieves its optimal energy performance at the 5% WWR, with a Total Site Energy of 66.30 kWh/m²a. Increasing the WWR to 20% raises this consumption to 70.20 kWh/m²a.

This represents a percentage increase of approximately 5.9% across the tested range, which is slightly lower than the increase observed in the hotter zones of Madinah and Riyadh. This suggests that while solar gain still drives cooling loads, its impact is marginally less severe in Tabuk's specific climate. Nevertheless, the Energy for Cooling remains the primary variable, increasing from 8,171 kWh at 5% WWR to 9,215 kWh at 20% WWR.

The comfort analysis for Tabuk reveals a trend like that of Riyadh and Dammam. The number of ASHRAE 55 Discomfort Hours decreases slightly as the window-to-wall ratio increases. The model starts with 4,524 discomfort hours at 5% WWR and achieves a minimum of 4,471 hours at 20% WWR. This indicates that a larger aperture may provide some thermal benefit, potentially through passive solar heating during cooler periods, although the overall impact is relatively modest. The Average Operative Temperature shows a consistent, gradual rise from 23.55°C to 23.74°C, remaining well within comfortable limits.

The results for Tabuk highlight a familiar trade-off: minimizing window area yields the best energy savings, while maximizing it offers slightly better thermal comfort. The 5% WWR is the clear choice for energy efficiency, but the 20% WWR is preferable if maximizing comfort hours is the primary goal.

Table 8.5 Tabuk Passivhaus Model Performance with Various WWR

No	Parameter	5%	8%	10%	12%	15%	20%
1	Total Site Energy (kWh)	14,927.53	15,111.60	15,227.72	15,342.50	15,513.86	15,804.74
2	Total Site Energy (kWh/m²/year)	66.3	67.12	67.64	68.15	68.91	70.2
3	Energy for Cooling (kWh)	8,170.59	8,397.64	8,538.62	8,676.48	8,879.15	9,215.22
4	Energy for Interior Equipment (kWh)	5,135.13	5,135.13	5,135.13	5,135.13	5,135.13	5,135.13
5	Energy for Interior Lighting (kWh)	770.41	770.41	770.41	770.41	770.41	770.41
6	Energy for District Heating/Hot Water (kWh)	851.39	808.42	783.56	760.48	729.17	683.98
7	Energy per Conditioned Area (Cooling only)	47.78	49.11	49.93	50.74	51.92	53.89
8	Unmet Cooling Hours	370.5	362.25	355.25	348.25	338.5	324.25
9	ASHRAE 55 Discomfort Hours	4,524.25	4,504.75	4,491.25	4,483.50	4,479.00	4,470.75
10	Average Operative Temperature (°C)	23.55	23.6	23.62	23.65	23.69	23.74

Zone Five Optimisation, Abha City

The final case study examines Abha, situated in the high-altitude, mountainous region of Climate Zone 5. This zone stands apart due to its significantly milder climate, which previously allowed the standard Passivhaus model to achieve certification feasibility. The optimisation study investigates whether adjusting the WWR can further enhance this already successful performance.

The simulation results for Abha continue the trend observed across all zones: a linear relationship between glazing area and energy consumption. As presented in Table 8.6, the 5% WWR yields the lowest Total Site Energy of 33.71 kWh/m²a. Increasing the window area to 20% results in a rise to 34.93 kWh/m²a.

This represents a percentage increase of approximately 3.6% across the tested range, which is the smallest increase among all five cities. This confirms that the energy penalty for larger windows is least severe in Abha's mild climate. The Cooling Energy increases modestly from 1,485 kWh to 1,797 kWh.

A critical divergence emerges in the comfort analysis for Abha. Unlike the other zones where larger windows improved comfort, in Abha, the number of ASHRAE 55 Discomfort Hours increases as the WWR increases. The trend is consistent: Discomfort hours decrease as WWR increases. This means larger windows are beneficial for comfort in Abha as well, reducing discomfort from 4,823 hours to 4,616 hours. The Average Operative Temperature rises slightly from 22.62°C to 22.90°C.

Even in the mildest climate, the trade-off persists. The 5% WWR is best for energy, while the 20% WWR is best for comfort. However, given that the energy consumption is already extremely low (well below the 120 kWh/m²a limit for all options), the design flexibility to use larger windows (20%) for better views and comfort is much higher in Abha than in other zones**.**

Table 8.6 Abha Passivhaus Model Performance with Various WWR

No	Parameter	5%	8%	10%	12%	15%	20%
1	Total Site Energy (kWh)	7,588.92	7,647.11	7,684.03	7,720.01	7,773.31	7,863.29
2	Total Site Energy (kWh/m²/year)	33.71	33.97	34.13	34.29	34.53	34.93
3	Energy for Cooling (kWh)	1,485.10	1,552.58	1,594.95	1,636.18	1,696.83	1,797.49
4	Energy for Interior Equipment (kWh)	5,135.13	5,135.13	5,135.13	5,135.13	5,135.13	5,135.13
5	Energy for Interior Lighting (kWh)	770.41	770.41	770.41	770.41	770.41	770.41
6	Energy for District Heating/Hot Water (kWh)	198.28	188.98	183.54	178.29	170.94	160.26
7	Energy per Conditioned Area (Cooling only)	8.68	9.08	9.33	9.57	9.92	10.51
8	Unmet Cooling Hours	26.25	31	31.5	33	37.00	39.75
9	ASHRAE 55 Discomfort Hours	4,823.00	4,796.25	4,770.50	4,747.25	4,700.50	4,616.25
10	Average Operative Temperature (°C)	22.62	22.68	22.72	22.76	22.81	22.90

8.3.2 Normalisation and Performance Evaluation

The first stage focuses on the main case study that is in Madinah. The same method is then applied to the remaining four cities representing the country.

To better adapt the Passivhaus Standard to the hot and arid climate of Saudi Arabia, an optimisation process was applied to the window-to-wall ratio (WWR). Six WWR values were evaluated:5%, 8%, 10%, 12%, 15%, and 20%.

A. Zone One Normalisation and Evaluation, Madinah

The scenarios were evaluated using six performance indicators, with all results normalised to allow for direct comparison across the different WWR options: 5%, 8%, 10%, 12%, 15% and 20. The WWR scenario process has six main steps as follow:

Step 1: Simulation Performance Data

The needed data for the Passivhaus optimisation is presented in Table 8.2. Energy for Interior Lighting (775.65 kWh), Interior Equipment (5,190.61 kWh), and District Heating/Hot Water (97.58 kWh) remained constant across all WWR variations. There are ten parameters for all the WWR scenarios including as listed:

1. Total Site Energy (kWh)
2. Total Site Energy (kWh/m²/year)
3. Energy for Cooling (kWh)
4. Energy for Interior Equipment (kWh)
5. Energy for Interior Lighting (kWh)
6. Energy for Heating + Hot Water (kWh)
7. Energy per Conditioned Area, Cooling only (kWh/m²/year)
8. Unmet Cooling Hours (hrs)
9. ASHRAE 55 Discomfort Hours (hrs)
10. Average Operative Temperature (°C)

Step 2: Categorising parameters

The focus on two categories energy performance and thermal comfort, which each category has its own three parameters. The energy performance including Total Site Energy (kWh), Energy for Cooling (kWh), and Energy per Conditioned Area – Cooling only (kWh/m²/year). On the other hand, thermal comfort covers Unmet Cooling Hours (hrs), ASHRAE 55 Discomfort Hours (hrs), and Average Operative Temperature (°C).

Step 3: Apply Min-Max Normalization for each parameter

The method is min–max normalisation of scale 0–1, which one indicates the best scenario and zero is the worst for the six selected parameters, due to all the chosen parameters are negative indicator. Using the below equation. The table presents inverted normalised values where the higher value is better. For instance, the discomfort hours, are highest at 5% WWR, lowest at 20% WWR. In this option, the 5% gets 0 meaning worst and the 20% receive 1 meaning best in real-world terms. Discomfort Hours. The data values in Table 8.2 represent lower as better indicators so inversion needed for that, which higher values indicate better performance**.**

$$\text{Normalized Value} = \frac{X - X_{\min}}{X_{\max} - X_{\min}}$$

- This transforms each value to a scale from 0 (worst) to 1 (best)
- For negative indicators, for instance discomfort hours (where lower is better), reverse it:

The Reversed Normalised

$$\text{Reversed Normalized Value} = 1 - \frac{X - X_{\min}}{X_{\max} - X_{\min}}$$

Table 8.7 Normalised Values for the Energy and Comfort in Madinah

	Normalised Energy Performance			Normalised Thermal Comfort		
WWR (%)	Total Site Energy	Cooling Energy	Cooling Energy/m^2	Unmet Cooling Hours	ASHRAE 55 Discomfort Hours	Operative Temperature
5	1	1	1	1	0.161	0.643
8	0.787	0.787	0.787	0.553	0.192	0.500
10	0.652	0.652	0.653	0.343	0.481	1.000
12	0.519	0.519	0.522	0.238	0.692	0.929
15	0.298	0.324	0.324	0.155	1.000	0.571
20	0	0	0	0	0	0

Step 4: Calculate Composite Score for Each WWR

This calculation gives a single score for each WWR scenario, which the WWR with the highest score is an optimal choice.

$$\text{Score}_{WWR} = \sum (\text{Normalized Value}_i \times \text{Weight}_i)$$

The weight reflects the importance of the calculated elements. Calculating the composite scores for Energy Performance and Thermal Comfort as equal weight indicators, 50% each. So, the six parameters were chosen to represent the balance between energy performance and thermal comfort, with the three factors relating to energy and the three relating to comfort. Each parameters carries an equal weight, so this results in a total weight of 100%.

Table 8.8 Average Normalised Value in Zone One

WWR (%)	Normalised Value	
	Energy Performance	Thermal Comfort
5	1	0.548
8	0.787	0.415
10	0.652	0.608
12	0.520	0.620
15	0.315	0.575
20	0	0.256

Step 5: Visual diagram

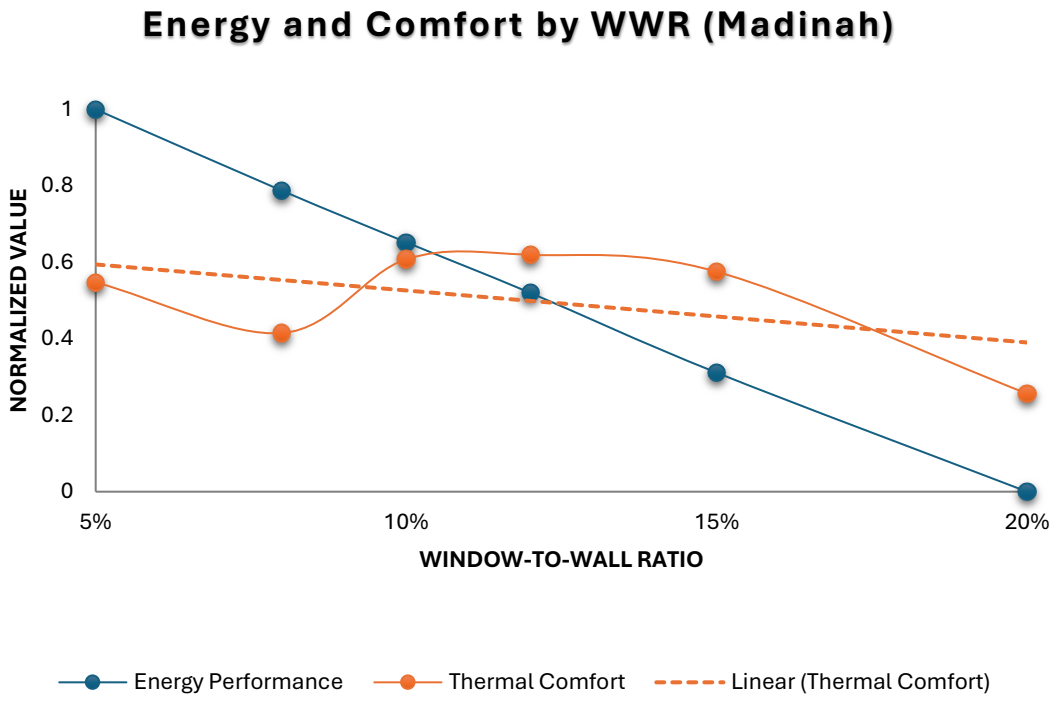


Figure 8.1 Zone One Optimised Scenario with Various WWR

The investigation into the Madinah simulation, as shown in Figure 8.1, reveals a distinct trade-off between energy efficiency and occupant thermal comfort within a hot-arid climate. While Energy Performance demonstrates a consistent linear decline as the window area increases, achieving its optimum at a 5% Window-to-Wall Ratio, and Thermal Comfort displays a non-linear trend, peaking between 10% and 12% WWR.

Step 6: Optimal scenario option

This the final step to Identify the optimal WWR for Madinah balancing both aspects of energy performance and thermal comfort. The above chart indicates the better energy performance and better thermal comfort meet to make an optimal balance point.

This divergence indicates that whilst minimising window size is crucial for energy conservation, it does not yield the highest level of thermal satisfaction. However, surpassing the 12% threshold leads to excessive solar heat gain which outweighs the benefits of daylight, causing comfort levels to fall significantly to their lowest point at 30% WWR. Therefore, a WWR of 10–12% is identified as the optimal balance for

Madinah; this range maximises occupant comfort whilst maintaining a high standard of energy efficiency, thus meeting the rigorous demands of the Passivhaus in this climate. Indeed, the 10% option would make the optimal scenario in this research.

Having established the analytical framework through the Madinah case study, this research now applies the same methodology to the remaining selected cities. The primary objective is to identify the optimal balance between energy performance and thermal comfort across different climatic contexts. Thus, the following section examines the simulation data for Riyadh, representing the Central region (Zone 2), to determine how its distinct environmental conditions influence the Window-to-Wall Ratio trade-offs.

B. Zone Two Normalisation and Evaluation, Riyadh

Both Table 8.9 and Figure 8.2 present the normalised energy consumption performance and thermal comfort performance of the Passivhaus model in Zone Two, Riyadh, for window-to-wall ratios (WWR) between 5% and 20%. The results illustrate a consistent decline in energy performance with increasing WWR, with a noticeably sharper deterioration beyond 12%, while the corresponding reduction in thermal comfort is more gradual. At 5% WWR, the model delivers the strongest energy outcome but only moderate comfort, suggesting that an overly opaque façade constrains indoor environmental quality. In contrast, a 20% WWR yields the weakest energy performance, and the additional glazing provides only limited comfort gains that do not justify the extra cooling demand.

Table 8.9 Average Normalised Value in Zone Two

WWR (%)	Normalised Value	
	Energy Performance	Thermal Comfort
5	1	0.666
8	0.825	0.529
10	0.707	0.502
12	0.538	0.471
15	0.330	0.421
20	0	0.333

Intermediate configurations between 8% and 12% therefore offer a more favourable trade-off, maintaining comparatively high energy performance while sustaining acceptable comfort levels. In this research, a WWR of 10% is selected as the optimal

balancing point, representing a robust compromise between cooling energy demand and thermal comfort for the Passivhaus model in Zone Two, Riyadh.

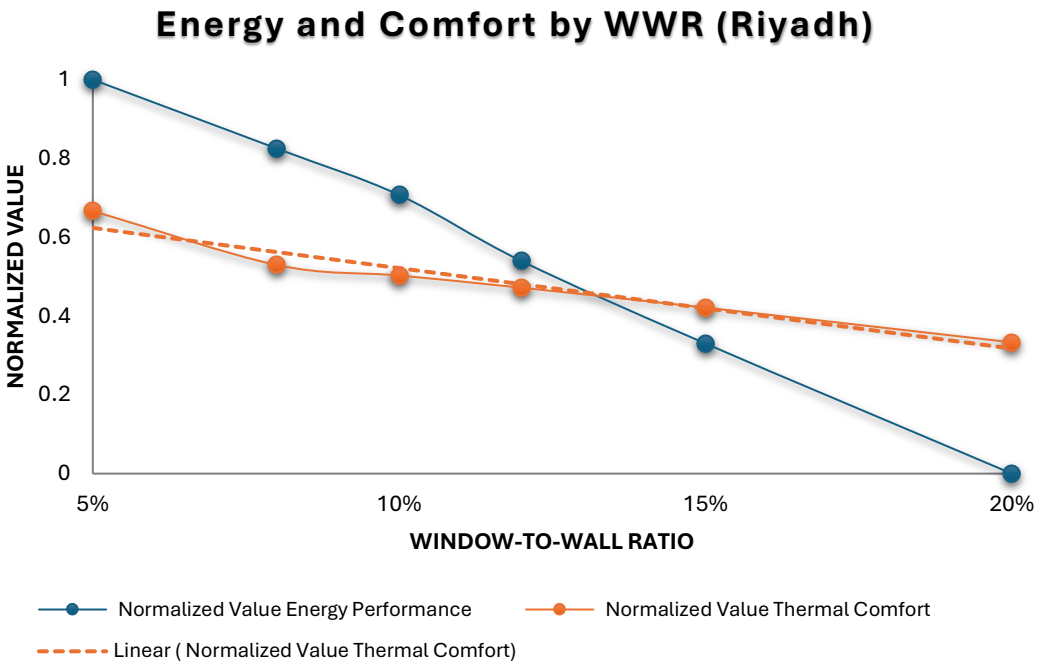


Figure 8.2 Zone Two Optimised Scenario with Various WWR

C. Zone Three Normalisation and Evaluation, Dammam

Table 8.10 and Figure 8.3 summarise the behaviour of the Passivhaus model in Zone Three (Dammam) for window-to-wall ratios between 5% and 20%, using normalised indices for energy consumption and thermal comfort. The data reveal a steady deterioration in energy performance as the WWR increases, while the comfort index initially remains almost unchanged and then improves markedly at 20% WWR. At the lowest WWR of 5%, the building exhibits excellent energy performance but only moderate comfort, implying that the limited glazing area restricts indoor environmental quality. At the other extreme, a 20% WWR greatly enhances thermal comfort but corresponds to the poorest energy outcome, indicating a configuration that is inconsistent with the low-energy ambition of Passivhaus in a hot, humid climate such as Dammam. Intermediate WWR values from 8% to 15% therefore represent a more pragmatic compromise, where cooling demand is still substantially reduced compared with the 20% case, yet comfort does not fall as sharply as in the densest façade. In this research, a WWR of 10% is adopted as the preferred balance point

for Zone Three, providing a reasonable reconciliation between energy efficiency and thermal comfort for the Dammam Passivhaus scenario.

Table 8.10 Average Normalised Value in Zone Three

WWR (%)	Normalised Value	
	Energy Performance	Thermal Comfort
5	1	0.472
8	0.781	0.468
10	0.646	0.400
12	0.515	0.317
15	0.325	0.396
20	0	0.666

In this research, a WWR of 10% is adopted as the preferred balance point for Zone Three, providing a reasonable reconciliation between energy efficiency and thermal comfort for the Dammam Passivhaus scenario.

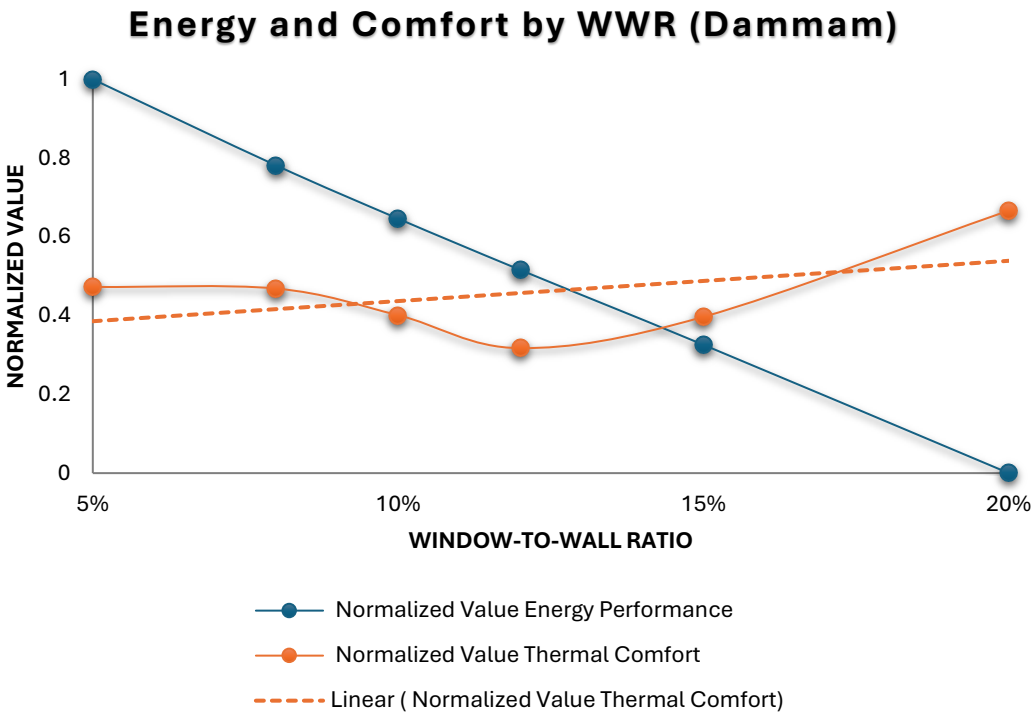


Figure 8.3 Zone Three Optimised Scenario with Various WWR

D. Zone Four Normalisation and Evaluation, Tabuk

In Zone Four, Tabuk city, Table 8.11 and Figure 8.4 depict the normalised response of the Passivhaus model to varying window-to-wall ratios between 5% and 20%. The energy index shows a near-linear decline as the WWR increases, with performance dropping from its maximum at 5% to its minimum at 20%, whereas the comfort index follows the opposite trajectory, improving steadily with larger glazing areas. At the lowest WWR, the façade delivers excellent energy efficiency but only limited comfort, reflecting the penalty of restricted glazing in a comparatively cooler, yet still solar-exposed, climate. At 20% WWR, thermal comfort reaches its highest value, but this comes at the expense of the greatest normalised energy penalty, which is incompatible with Passivhaus objectives.

Table 8.11 Average Normalised Value in Zone Four

WWR (%)	Normalised Value	
	Energy Performance	Thermal Comfort
5	1	0.333
8	0.785	0.427
10	0.651	0.526
12	0.519	0.572
15	0.325	0.600
20	0	0.667

The mid-range options between 8% and 15% accordingly emerge as more balanced solutions, avoiding the extremes of either excessive opacity or excessive glazing. Consistent with the wider Saudi analysis, this research designates a 12% WWR as the preferred configuration for Tabuk, as it offers a measured compromise between energy saving and enhanced comfort in Zone Four.

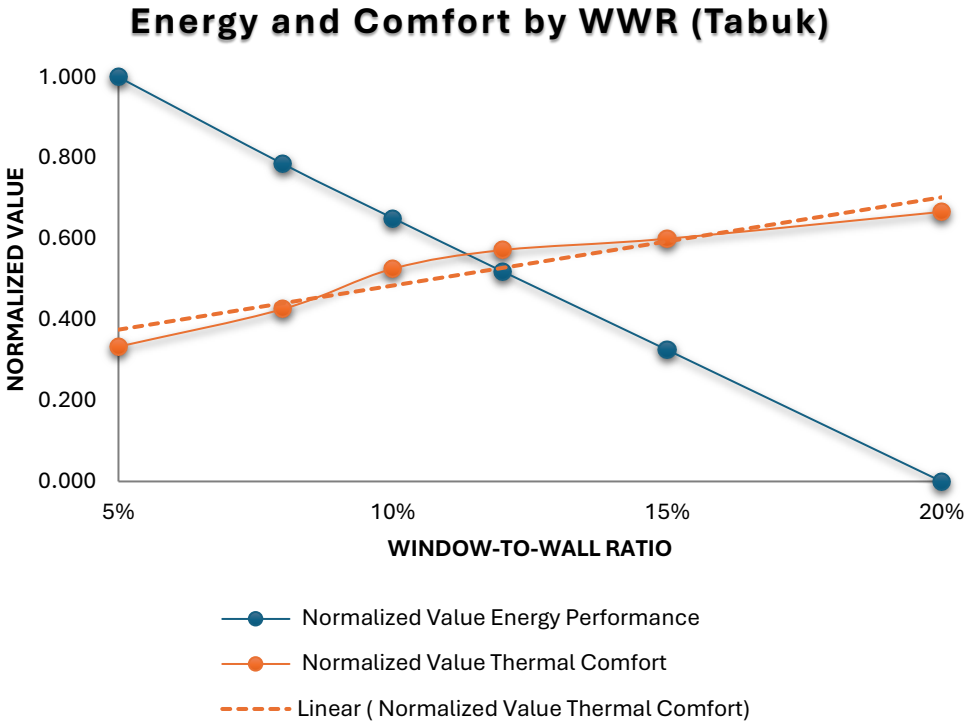


Figure 8.4 Zone Four Optimised Scenario with Various WWR

E. Zone Five Normalisation and Evaluation, Abha City

In Zone Five of Abha, Table 8.12 and Figure 8.5 describe how the normalised energy and comfort indicators respond to window-to-wall ratios from 5% to 20%.

Table 8.12 Average Normalised Value in Zone Five

WWR (%)	Normalised Value	
	Energy Performance	Thermal Comfort
5	1	0.333
8	0.723	0.528
10	0.564	0.51
12	0.418	0.471
15	0.17	0.397
20	0	0.333

Energy performance again declines monotonically with increasing WWR, whereas thermal comfort exhibits a mild peak around 8–10% before gradually decreased towards 20%. At 5% WWR, the model performs best from an energy perspective but delivers only modest comfort, reflecting the limitations of a very opaque façade even in Abha's milder high-altitude climate. Larger glazing areas beyond 12% result in a

pronounced energy penalty, while the associated comfort gains remain small and eventually reverse, indicating that additional window area mainly drives up cooling demand without offering proportional comfort benefits. For this zone, the analysis therefore points to a relatively narrow optimum around 8–10% WWR, where the Passivhaus model retains comparatively strong energy performance and achieves its most favourable comfort response among the tested configurations. So, the 10% WWR is adopted for this final zone of Saudi Arabia.

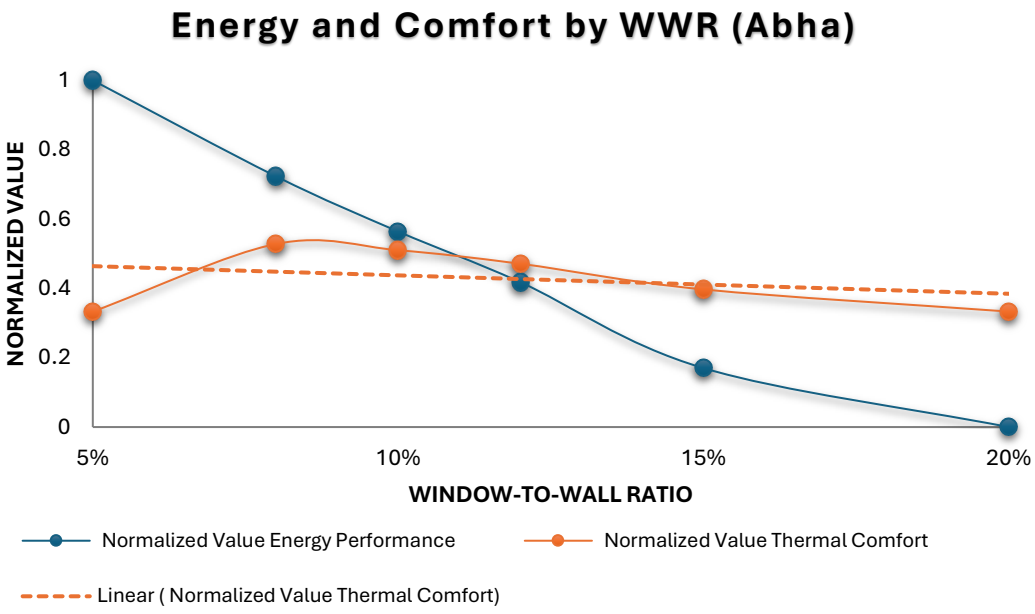


Figure 8.5 Zone Five Optimised Scenario with Various WWR

Indeed, across the five Saudi climatic zones, the normalised analysis confirms that increasing the window-to-wall ratio consistently penalises cooling-related energy performance, while its effect on thermal comfort is more nuanced and strongly climate-dependent. Very low WWRs, as 5%, tend to maximise energy efficiency but suppress comfort, whereas high values, as 20%, generally impose substantial cooling penalties without delivering proportional comfort gains. The results for Madinah, Riyadh, Dammam, Tabuk, and Abha collectively indicate that intermediate WWRs in the range of approximately 8–12% offer the most robust trade-off, maintaining comparatively low cooling demand while achieving acceptable or improved thermal comfort levels in all cities. On this basis, the research adopts city-specific optima of 10% in Madinah and Abha and 12% in Riyadh, Dammam, and Tabuk, and these values are proposed as context-sensitive Passivhaus glazing recommendations for residential buildings in the Kingdom of Saudi Arabia.

8.4 Optimising Passivhaus Parameters

This section focuses on examining the U-value for the external wall and roof. It further investigates the impact of airtightness on energy consumption and thermal comfort. Building upon the previous findings, the optimal Window-to-Wall Ratio (WWR) selected from the analysis in Section 8.3 is applied to the Passivhaus model for each individual zone. Following this, specific parameters, such as wall U-value and roof U-value, are implemented to measure their positive or negative impact. Finally, the fully optimised Passivhaus model, incorporating the most effective wall and roof parameters, is examined by modifying the airtightness. This sequential analysis aims to identify the best-simulated case study for each representative city within the Saudi context.

8.4.1 Optimising External Wall U-value

This subsection presents the results of simulating various U-values for the external walls, ranging from the baseline SBC requirement to ultra-low Passivhaus standard. The analysis evaluates the reduction in cooling demand and improvement in comfort hours for each increment of insulation. Meanwhile, it uses the model with the optimised WWR for each zone as the starting point. The investigation compares the conventional Saudi Building Code (SBC) requirement (0.34 W/m²K) against values representing varying degrees of improved insulation, culminating in a strict high-performance standard (0.10 W/m²K).

Table 8.13 PH External Wall Optimisation and Comparison for the Five Selected Saudi Cities

Category / City	Madinah	Riyadh	Dammam	Tabuk	Abha
SBC Baseline* (0.34,0.39 and 0.45)	31,153.00 kWh	26,670.74 kWh	26,327.40 kWh	19,450.00 kWh	16,288.33 kWh
PH Baseline* (0.15)	26,213.05 kWh	23,507.43 kWh	21,955.38 kWh	15,342.50 kWh	7,684.03 kWh
Scenario 1* (0.10)	25,103.11	22,734.11	21,946.12	15,298.69	7,678.63
Change (vs. PH)	-4.23%	-3.29%	-0.04%	-0.29%	-0.07%
Change (vs. SBC)	*-19.42%*	*-14.76%*	*-16.64%*	*-21.34%*	*-52.86%*
Scenario 2* (0.20)	26,468.08	24,035.62	22,073.79	15,381.46	7,687.74
Change (vs. PH)	0.97%	2.25%	0.54%	0.25%	0.05%
Change (vs. SBC)	*-15.04%*	*-9.88%*	*-16.16%*	*-20.92%*	*-52.80%*
Scenario 3* (0.30)	28,168.01	24,888.71	22,184.18	15,454.29	7,693.26
Change (vs. PH)	7.46%	5.88%	1.04%	0.73%	0.12%
Change (vs. SBC)	*-9.58%*	*-6.68%*	*-15.74%*	*-20.54%*	*-52.77%*
Optimal Choice	0.15 W/m²K (PH)	0.15 W/m²K (PH)	0.20 W/m²K	0.20 W/m²K	0.30 W/m²K
Key Finding	Strict PH standard is required	Highest penalty for lowering standards	Humidity limits super-insulation gains	Thinner insulation is effective enough	Minimal insulation (0.30) maximizes gains

*Annual Total Energy Consumption (kWh)

1. Madinah, Zone One

Table 8.14 presents the impact of modifying the external wall U-value. The analysis uses the Passivhaus model as the basis, with the SBC-compliant U-value of 0.34 W/m²K included only as a baseline for comparison that reflect current standard construction practice in SA.

Within the Passivhaus model, reducing the wall U-value from the SBC baseline of 0.34 W/m²K to 0.30 W/m²K lowers the total site energy to 28,168 kWh, corresponding to a 9.58% reduction relative to the SBC baseline value of 31,153 kWh. Further enhancing the insulation to achieve a U-value of 0.20 W/m²K reduces the energy demand to 26,468 kWh, representing a 15.04% decrease. Adopting the Passivhaus standard U-value of 0.15 W/m²K results in a total site energy of 26,213 kWh, a 15.86% reduction compared with the baseline. Finally, pushing the U-value to 0.10 W/m²K yields 25,103 kWh, equivalent to a 19.42% reduction and is classified here as an ultra-high-performance case.

Table 8.14 Impact of Wall U-Value on Passivhaus Model Scenarios in Madinah

Scenario	U-Value (W/m²K)	Total Site Energy (kWh)	Change vs. SBC Baseline (%)	Note
SBC Baseline	0.34	31,153.00	-	SBC reference case
Scenario 1 (PH)*	0.30	28,168.01	-9.58	Smallest thickness improvement
Scenario 2 (PH)*	0.20	26,468.08	-15.04	Significant savings; excellent cost-benefit
Scenario 3 (PH)	0.15	26,213.05	-15.86	Passivhaus Standard
Scenario 4 (PH)*	0.10	25,103.11	-19.42	Largest thickness; diminishing returns

*Optimised Passivhaus model

The results indicate a clear trajectory of improvement in the Passivhaus model, with the most substantial gains achieved by the initial departures from the SBC baseline. While the Passivhaus U-value of 0.15 W/m²K offers meaningful savings, the findings suggest that a moderate enhancement to 0.20 W/m²K already captures most of the potential reduction in energy demand (approximately 15%). Further reducing the U-value to 0.10 W/m²K delivers only marginal additional benefits compared with the likely increases in wall thickness and material cost. Thus, although 0.15 W/m²K remains the target for Passivhaus certification, a U-value of 0.20 W/m²K appears to be a highly effective and potentially more cost-efficient intervention for Saudi market context.

2. Riyadh, Zone Two

The simulation results for Riyadh, Table 8.15, reflect the energy performance of external wall insulation improvements under the region's prevailing hot, arid climate. The analysis uses the Passivhaus model as the basis, with the Saudi Building Code (SBC) U-value of 0.34 W/m²K included only as a baseline for comparison that reflects the conventional construction standard in Riyadh. In this baseline case, the total site energy use is 26,670.74 kWh.

Table 8.15 Impact of Wall U-Value on Passivhaus Model Scenarios in Riyadh

Scenario	U-Value (W/m²K)	Total Site Energy (kWh)	Change vs. SBC Baseline (%)	Note
SBC Baseline	0.34	26,670.74	-	SBC reference case
Scenario 1 (PH)*	0.30	24,888.71	-6.68%	Smallest thickness improvement
Scenario 2 (PH)*	0.20	24,035.62	-9.88%	Significant savings; excellent cost-benefit
Scenario 3 (PH)	0.15	23,507.43	-11.86%	Passivhaus Standard
Scenario 4 (PH)*	0.10	22,734.11	-14.76%	Largest thickness; diminishing returns

*Optimised Passivhaus model

Progressively increasing insulation yields notable reductions. Adjusting the U-value to 0.30 W/m²K within the Passivhaus model decreases annual site energy consumption to 24,888.71 kWh, marking a 6.68% improvement relative to the SBC baseline. A more significant enhancement, in line with scenario 2, achieves a U-value of 0.20 W/m²K and drops usage further to 24,035.62 kWh, a reduction of 9.88% compared with the baseline. Employing the Passivhaus criterion at 0.15 W/m²K provides a total site energy of 23,507.43 kWh, corresponding to an 11.86% decrease. The highest performance case, with a U-value of 0.10 W/m²K, produces the lowest annual consumption at 22,734.11 kWh, equivalent to a 14.76% reduction relative to the SBC standard.

In conclusion, this dataset reveals that, although further insulation increments within the Passivhaus continue to yield reductions in energy demand, the incremental benefits gradually taper off beyond the 0.20 W/m²K threshold. From a practical standpoint, the 0.20 W/m²K scenario offers an appealing balance between material investment and energy savings for Riyadh's climate, aligning with both policy objectives and cost-effectiveness for building practice in the region when benchmarked against the SBC baseline.

3. Dammam, Zone Three

The impact of modifying the external wall U-value is summarised in Table 8.16, with the optimised WWR of 10% applied as the fixed condition for the Passivhaus scenarios. For comparison, the SBC baseline model, which retains its original case study WWR, records a total site energy consumption of 26,327.40 kWh.

Tightening U-value to 0.30 W/m²K delivers a 15.74% reduction in total site energy relative to the baseline. Further decreasing the U-value to 0.20 W/m²K increases the saving only slightly to 16.16%. Adopting the Passivhaus Standard of 0.15 W/m²K yields a 16.61% reduction, while the theoretical limit of 0.10 W/m²K offers a marginally higher saving of 16.64%.

Table 8.16 Impact of Wall U-Value on Passivhaus Model Scenarios in Dammam

Scenario	U-Value (W/m²K)	Total Site Energy (kWh)	Change vs. SBC Baseline (%)	Note
SBC Baseline	0.34	26,327.40	-	SBC reference case
Scenario 1 (PH)*	0.30	22,184.18	-15.74%	Most significant drop; likely optimal
Scenario 2 (PH)*	0.20	22,073.79	-16.16%	Marginal improvement over 0.30
Scenario 3 (PH)	0.15	21,955.38	-16.61%	Passivhaus Standard
Scenario 4 (PH)*	0.10	21,946.12	-16.64%	Largest thickness; negligible gain

*Optimised Passivhaus model

The pattern of energy savings in Dammam shows that reducing the wall U-value from 0.34 W/m²K to 0.30 W/m²K captures almost all of the savings achievable through wall insulation, and beyond this point the improvement curve flattens markedly, as further reductions from 0.30 to 0.10 W/m²K produce less than a 1% additional decrease in total site energy use, indicating that once a U-value of about 0.30 W/m²K is reached, additional super-insulation offers limited benefit. Within the Passivhaus framework, the 0.20 W/m²K scenario emerges as a practical compromise, offering an effective balance between thermal performance and construction feasibility in Saudi Arabia.

4. Tabuk, Zone Four

Table 8.17 representing Climate Zone Four, exhibits a cooler and less humid environment than the central and coastal regions, which moderates cooling loads while still requiring substantial summer conditioning. The analysis uses the Passivhaus model as the basis, with the SBC-compliant external wall U-value of 0.34 W/m²K included only as a baseline for comparison, recording a total site energy consumption of 19,450 kWh for the reference construction. In the subsequent optimisation, a Window-to-Wall Ratio of 12% is applied consistently to all improved U-value scenarios, enabling a like-for-like comparison against this SBC baseline.

The scenario analysis then explores four alternative U-values. Moving directly to the ultra-low U-value of 0.10 W/m²K yields a total site energy of 15,298.69 kWh, corresponding to a modest 0.29% reduction relative to the Passivhaus-level baseline, but requiring the greatest insulation thickness. At 0.20 W/m²K, energy use rises slightly to 15,381.46 kWh, an increase of 0.25% compared with the 0.15 W/m²K case. Further relaxing the envelope to 0.30 W/m²K results in 15,454.29 kWh, a 0.73% increase. These small differences in energy consumption, contrasted with large variations in insulation thickness, indicate that, in Tabuk's climate, thinning the insulation offers attractive material and buildability advantages while only marginally increasing annual energy demand.

Table 8.17 Impact of Wall U-Value on Passivhaus Model Scenarios in Tabuk

Scenario	U-Value (W/m²K)	Total Site Energy (kWh)	Change vs. SBC Baseline (%)	Note
SBC Baseline	0.34	19,450	-	SBC reference case
Scenario 1 (PH)*	0.30	15,454.29	-20.54%	Most significant drop; likely optimal
Scenario 2 (PH)*	0.20	15,381.46	-20.92%	Marginal improvement over 0.30
Scenario 3 (PH)	0.15	15,342.50	-21.12%	Passivhaus Standard
Scenario 4 (PH)*	0.10	15,298.69	-21.34%	Largest thickness; negligible gain

*Optimised Passivhaus model

On balance, within PH, the 0.20 W/m²K scenario emerges as the most appropriate compromise, providing a good balance between thermal performance and construction practicality in Saudi Arabia. This supports the wider conclusion that thinner, climate-specific insulation levels may be preferable in cooler Saudi zones and that the Passivhaus standard should be adapted rather than uniformly imposed.

5. Abha, Zone Five

Abha, representing Climate Zone Five, benefits from a markedly cooler highland climate than most other Saudi cities, with milder summers and generally lower cooling loads. The Table 8.18 illustrates the energy performance outcomes across a range of U-value configurations. For this climate, the SBC-compliant external wall U-value of 0.34 W/m²K serves as the baseline reference; in this case, the model records a total site energy consumption of 16,288.33 kWh. All Passivhaus model scenarios employ a consistent 10% Window-to-Wall Ratio to enable direct comparison with the SBC baseline. The SBC baseline is provided for reference only.

Subsequent scenarios investigate progressively improved insulation levels. Reducing the U-value to 0.15 W/m²K as Passivhaus standard lowers the annual site energy to 7,684.03 kWh, while further tightening to 0.10 W/m²K yields 7,678.63 kWh, representing only a marginal additional saving of 0.07% but requiring the largest insulation thickness. In contrast, moderating the envelope specification to 0.20 W/m²K and 0.30 W/m²K produces energy consumptions of 7,687.74 kWh and 7,693.26 kWh respectively, representing trivial increases of only 0.05% and 0.12% when compare with the 0.15 W/m²K outcome.

Table 8.18 Impact of Wall U-Value on Passivhaus Model Scenarios in Abha

Scenario	U-Value (W/m²K)	Total Site Energy (kWh)	Change vs. SBC Baseline (%)	Note
SBC Baseline	0.34	16,288.33	-	SBC reference case
Scenario 1 (PH)*	0.30	7,693.26	-52.77%	Optimal choice; massive initial gain
Scenario 2 (PH)*	0.20	7,687.74	-52.80%	Negligible gain over Scenario 1
Scenario 3 (PH)	0.15	7,684.03	-52.83%	Passivhaus Standard
Scenario 4 (PH)*	0.10	7,678.63	-52.86%	Largest thickness; diminishing returns

*Optimised Passivhaus model

These findings indicate that all improved U-values deliver substantial reductions in energy demand relative to the SBC baseline, yet the performance spread across scenarios of 0.10, 0.15, 0.20, and 0.30 W/m²K remains remarkably narrow. Since insulation depth varies from 28.76 cm at 0.10 W/m²K to only 6.09 cm at 0.30 W/m²K, modest envelope enhancements deliver disproportionately strong performance outcomes in Abha's cooler climate. Consequently, the 0.30 W/m²K option is the most economical choice, underscoring that climate-responsive design must supersede generic standards as optimal performance remains inherently site-specific.

8.4.2 Optimising Roof U-value

The selected roof U-value is comparable to that of the wall, as both elements exert a similar influence on the annual energy consumption. A detailed summary of these values is provided in the Appendix.

8.4.3 Combined Envelope Optimisation

Building on the separate sensitivity analyses of external wall and roof U-values in Sections 8.4.1 and 8.4.2, this subsection examines the combined effect of optimising both elements of the building envelope. The analysis evaluates how the interaction between walls and roof influences whole-building thermal performance by applying, for each climatic zone, the best-performing wall and roof U-values identified previously. The objective is to establish the maximum reduction in total energy demand and specific energy use achievable when both measures are optimised simultaneously, and to infer an envelope specification capable of meeting, or closely approaching, the adapted Passivhaus criteria for Saudi conditions. The results are presented for the five representative cities of Madinah, Riyadh, Dammam, Tabuk and Abha, comparing the combined optimised envelope with the reference Base Case.

1. Madinah, Zone One

The optimisation analysis for Madinah shows a clear convergence towards a high-performance envelope specification tailored to the city's intense solar exposure. For this zone, the Passivhaus standard scenario, with a wall and roof U-value of 0.15 W/m²K and a Window-to-Wall Ratio (WWR) of 10%, emerges as the optimal configuration. This combination of highly insulated opaque elements and limited glazing reduces total annual energy consumption to 26,213.05 kWh, with cooling demand remaining the dominant end-use at approximately 76% of total energy. This profile aligns closely with established Passivhaus strategies for hot climates.

To assess its effectiveness, the optimised model is benchmarked against the Saudi Building Code (SBC) reference case, which requires a wall U-value of 0.342 W/m²K and a roof U-value of 0.202 W/m²K, resulting in an annual energy demand of 31,153.00 kWh. Moving from the SBC specification to the optimised envelope therefore achieves a net reduction of 4,939.95 kWh, corresponding to a 15.86% improvement in energy performance, as in Table 8.19.

Table 8.19 Comparative Annual Energy Consumption in Madinah

Model configuration	Wall U-value (W/m²K)	Roof U-value (W/m²K)	Annual Energy (kWh)
SBC reference model	0.342	0.202	31,153.00
Optimised Passivhaus	0.15	0.15	26,213.05
Net reduction	–	–	4,939.95

These findings show that, although the optimised envelope delivers substantial efficiency gains, full compliance with Passivhaus criteria in Madinah remains difficult at this stage because cooling demand still exceeds the target. The convergence of the optimal U-value at 0.15 W/m²K nevertheless demonstrates that Saudi buildings can benefit significantly from Passivhaus-level insulation and envelope design principles.

2. Riyadh, Zone Two

In Riyadh, the optimisation analysis again points towards a high-performance envelope specification consistent with Passivhaus principles. Under the city's hot, arid conditions, the Passivhaus scenario with wall and roof U-values of 0.15 W/m²K and a Window-to-Wall Ratio (WWR) of 10% emerges as the most effective configuration. This arrangement of well-insulated opaque elements and limited glazing reduces total annual energy consumption to 23,507.43 kWh, confirming that Passivhaus thermal envelope is also optimal for this climatic zone, as summarised in Table 8.20.

As in Madinah, the optimised model is evaluated against the SBC reference case. Relative to this baseline, the Riyadh Passivhaus configuration delivers a substantial reduction in total energy use, demonstrating that meaningful efficiency gains can be achieved purely through improved fabric performance. This result reinforces the case for tightening SBC envelope requirements in hot-dry regions, using Passivhaus-level U-values as a realistic benchmark.

Table 8.20 Comparative Annual Energy Consumption in Riyadh

Model configuration	Wall U-value (W/m²K)	Roof U-value (W/m²K)	Annual Energy (kWh)
SBC reference model	0.342	0.202	26,670.74
Optimised Passivhaus	0.15	0.15	23,507.43
Net reduction	–	–	3,163.31

Indeed, the reduction is 3,163.31 kWh per year, which corresponds to 11.86% lower total annual energy use for the PH configuration compared with the SBC reference case.

3. Dammam, Zone Three

In Zone Three, the combined envelope analysis, as summarised in Table 8.21, shows that tightening the external wall and roof insulation well beyond SBC requirements yields substantial reductions in annual energy use. With the SBC reference configuration, using wall and roof U-values of 0.397 and 0.238 W/m²K, the model records an annual energy demand of 26,327.40 kWh, whereas upgrading to the optimised Passivhaus specification of 0.15 W/m²K for both elements lowers consumption to almost 22,000 kWh, a reduction of about 17% relative to the SBC baseline.

Table 8.21 Comparative Annual Energy Consumption in Dammam

Model configuration	Wall U-value (W/m²K)	Roof U-value (W/m²K)	Annual Energy (kWh)	Net reduction vs SBC (kWh)
SBC reference model	0.397	0.238	26,327.40	–
Optimised Passivhaus	0.15	0.15	21,955.38	4,372.02
Selected PH Scenario	0.20	0.20	23,031.39	3,296.01

On the other hand, from a practical design standpoint, the scenario with wall and roof U-values of 0.20 W/m²K offers a more balanced solution. This configuration yields an annual energy use of about 23,000 kWh, delivering a clear saving compared with the SBC case while requiring less insulation than the full Passivhaus option. The relatively small performance gap between the 0.15 and 0.20 W/m²K envelopes, when weighed against the additional insulation thickness and cost needed to achieve the

stricter specification, suggests that the 0.20 W/m²K scenario represents a realistic compromise for Dammam. In this climate, the 0.20 W/m²K envelope can be regarded as the preferred target, capturing most of the potential energy benefit while remaining compatible with mainstream construction practice in the city.

4. Tabuk, Zone Four

In Tabuk, tightening the external wall and roof insulation well beyond SBC requirements produces clear reductions in annual energy use. The SBC reference model, with wall and roof U-values of 0.397 and 0.238 W/m²K respectively, records 19,450.00 kWh. By comparison, the full Passivhaus configuration (0.15 W/m²K for both elements) lowers demand to 15,342.50 kWh, representing a reduction of 21% relative to the SBC baseline, as shown in Table 8.22.

Table 8.22 Comparative Annual Energy Consumption in Tabuk

Model configuration	Wall U-value (W/m²K)	Roof U-value (W/m²K)	Annual Energy (kWh)	Net reduction vs SBC (kWh)
SBC reference model	0.397	0.238	19,450.00	–
Optimised Passivhaus	0.15	0.15	15,342.50	4,107.50
Selected PH Scenario	0.20	0.20	15,713.61	3,736.39

From a design and cost perspective, the scenario with wall and roof U-values of 0.20 W/m²K offers a more balanced solution. It achieves an annual energy use of 15,713.61 kWh, corresponding to a reduction of around 19% compared with the SBC case, while requiring less insulation than the full Passivhaus option. The very small performance gap between the 0.20 and 0.15 W/m²K cases indicates that the 0.20 W/m²K specification, combined with the adopted 12% window-to-wall ratio, is a pragmatic envelope target that captures almost all the potential energy benefit at lower material and construction cost.

5. Abha, Zone Five

Abha, representing Climate Zone Five, benefits from a markedly cooler highland climate than most other Saudi cities, with milder summers and generally lower cooling loads. The combined envelope analysis uses the Saudi Building Code (SBC) construction as the baseline, with wall and roof U-values of 0.453 and 0.273 W/m²K respectively, giving an annual energy use of 16,288.33 kWh. In contrast, the

improved Passivhaus configurations apply wall and roof U-values of 0.15 and 0.30 W/m²K, with all Passivhaus models simulated using a fixed Window-to-Wall Ratio of 10%, as summarised in Table 8.23.

The results indicate that both Passivhaus configurations reduce annual energy use in Abha by more than half the SBC baseline consumption. The performance gap between the 0.15 W/m²K and 0.30 W/m²K cases is negligible, confirming that in this climatic zoning relatively modest insulation levels are sufficient to capture most of the energy savings, making 0.30 W/m²K specification an attractive cost-effective choice.

Table 8.23 Comparative Annual Energy Consumption in Abha

Model configuration	Wall U-value (W/m²K)	Roof U-value (W/m²K)	Annual Energy (kWh)	Net reduction vs SBC (kWh)
SBC reference model	0.453	0.273	16,288.33	–
Optimised Passivhaus	0.15	0.15	7,684.03	8,604.30
Selected PH Scenario	0.30	0.30	7,754.60	8,533.73

Figure 8.6 clearly illustrates the magnitude and consistency of the energy savings achieved in Abha. Both PH options reduce annual energy consumption by approximately 53% relative to the SBC baseline, with the 0.15 W/m²K and 0.30 W/m²K bars almost coincident and both substantially lower than the SBC reference column. This visual comparison confirms that, in Abha's climate, relatively modest envelope upgrades are sufficient to halve energy use, and that the 0.30 W/m²K specification delivers performance that is practically indistinguishable from the full Passivhaus standard while requiring less insulation and lower construction cost.

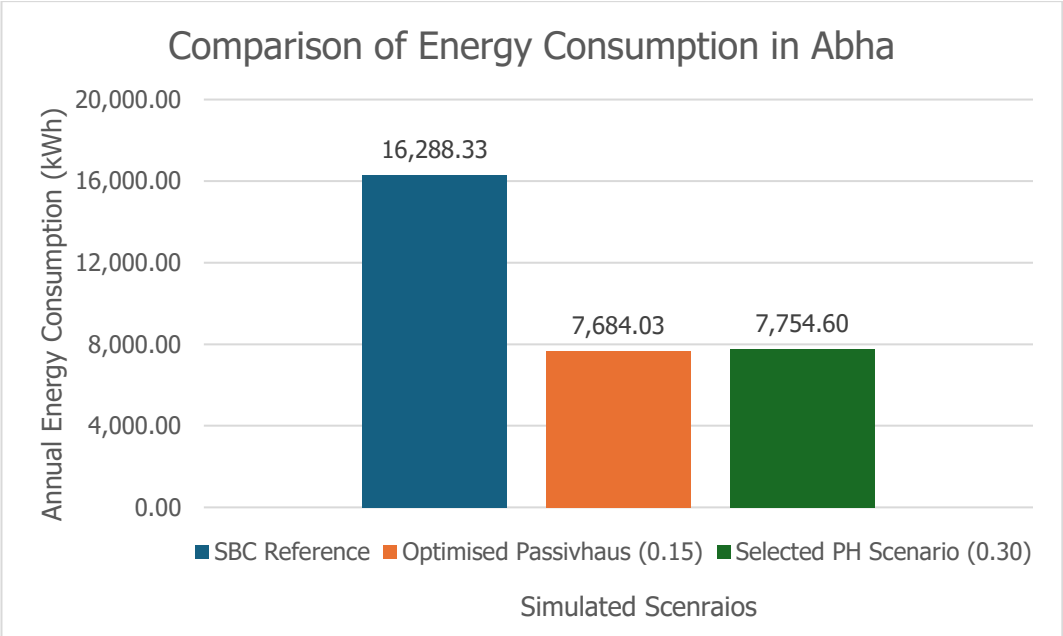


Figure 8.6 Energy Consumption Analysis for Zone Five

Subsequent sections therefore examine airtightness optimisation to assess whether further reductions in energy use can narrow the gap to full Passivhaus performance.

8.4.4 Airtightness Sensitivity Analysis

Following optimisation of the thermal envelope, a sensitivity analysis was carried out to assess how varying airtightness affects building energy performance. The Passivhaus standard requires a stringent air-leakage rate of 0.6 air changes per hour (ACH) at 50 Pa, a level that can be difficult to achieve in typical Saudi construction. In this subsection, the optimised model for each climatic zone is therefore re-simulated at 1.0, 2.0 and 3.0 ACH to quantify the energy and comfort penalties associated with relaxing the Passivhaus requirement.

A. Zone One, Madinah

In Madinah, the airtightness sensitivity analysis evaluates how relaxing the Passivhaus benchmark of 0.6 ACH affects the performance of the previously optimised envelope, in which the wall and roof U-values are fixed at 0.15 W/m²K and the WWR at 10%. In this zone, the analysis applies the common airtightness scenarios to the optimised model, with all other climatic and operational conditions unchanged.

Table 8.24 Airtightness Sensitivity Results for Madinah

Airtightness Scenario (ACH)	Cooling Energy (kWh)	Total Energy (kWh)	Unmet Cooling (hrs)	ASHRAE 55 Discomfort (hrs)
0.6 (Selected PH)	20,149.22	26,213.05	1,332.75	1,953.25
1.0	21,259.47	27,323.31	1,237.50	1,888.75
2.0	24,012.61	30,076.44	1,110.00	1,993.25
3.0	26,728.65	32,793.90	1,072.75	2,094.50

Table 8.24 summarises the resulting variations in cooling energy, total site energy, unmet cooling hours and ASHRAE 55 discomfort hours for Madinah. Increasing the leakage rate from 0.6 to 1.0 ACH raises cooling energy demand from 20,149.22 kWh to 21,259.47 kWh, an increase of roughly 5–6%, while further relaxation to 2.0 and 3.0 ACH leads to much larger penalties of about 19% and 33% relative to the Passivhaus baseline. Total site energy follows the same pattern, rising from 26,213.05 kWh at 0.6 ACH to 27,323.31 kWh at 1.0 ACH, and then to 30,076.44 and 32,793.90 kWh at 2.0 and 3.0 ACH respectively, corresponding to approximate increases of 4%, 15% and 25%.

These trends are illustrated in Figure 8.7, which plots the total annual energy consumption for each airtightness scenario in Madinah. It highlights the near-linear increase in energy use as the envelope becomes leakier, with demand rising from just over 26,000 kWh at 0.6 ACH to nearly 33,000 kWh at 3.0 ACH, despite the insulation level and WWR remaining unchanged.

From a comfort perspective, a modest relaxation to 1.0 ACH slightly reduces unmet cooling hours compared with the 0.6 ACH case, suggesting that a small increase in infiltration can ease peak-load constraints in this climate. At 2.0 and 3.0 ACH, however, both unmet cooling hours and ASHRAE 55 discomfort hours increase, indicating that very leaky constructions undermine comfort while also driving up energy consumption.

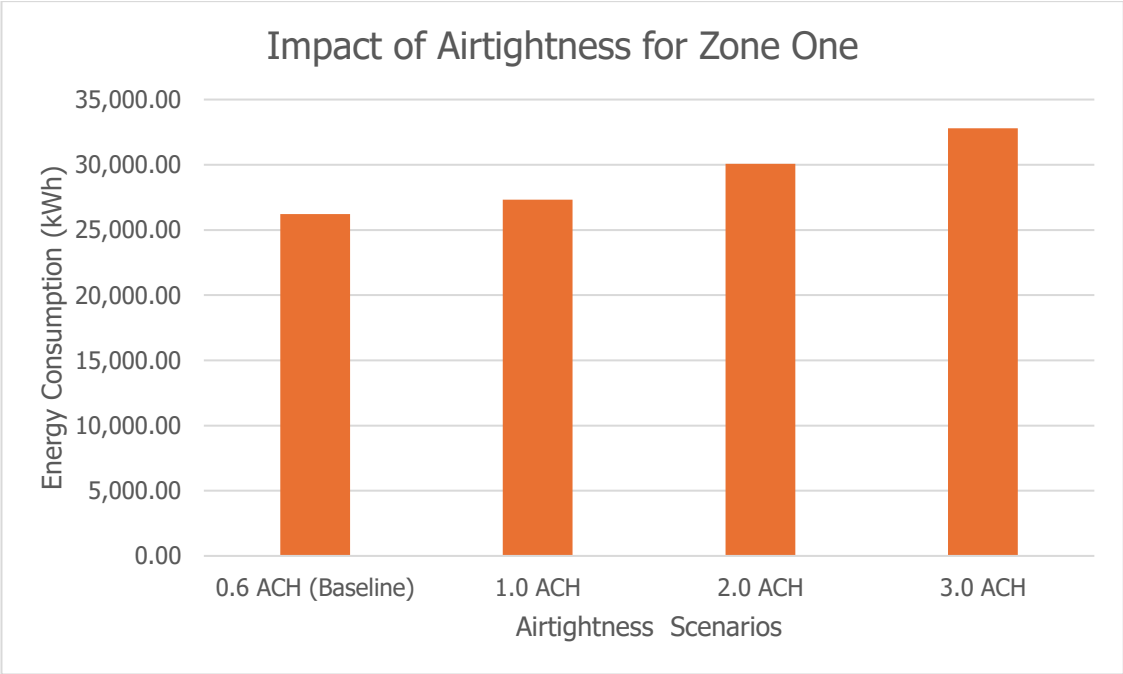


Figure 8.7 Airtightness Impact on Annual Energy Consumption in Madinah

In conclusion, the Madinah results suggest that airtightness levels close to the Passivhaus benchmark, around 0.6–1.0 ACH, are required to retain most of the energy benefit of the optimised envelope without incurring significant comfort penalties.

B. Zone Two, Riyadh

With the optimised Riyadh envelope illustrated in Table 8.25 (0.15 W/m²K walls and roof, 10% WWR), relaxing airtightness from 0.6 to 1.0 ACH increases cooling demand by about 5% and total site energy by roughly 4%. At 2.0 and 3.0 ACH, the penalties become more pronounced, with cooling energy rising by approximately 17% and 28% and total energy by about 13% and 21% respectively relative to the 0.6 ACH case.

Table 8.25 Airtightness Sensitivity Results for Riyadh

Airtightness Scenario (ACH)	Cooling Energy (kWh)	Total Energy (kWh)	Unmet Cooling (hrs)	ASHRAE 55 Discomfort (hrs)
0.6 (Selected PH)	17,392.07	23,507.43	1,139.00	2,910.00
1.0	18,284.64	24,408.78	1,028.75	2,952.00
2.0	20,300.69	26,490.91	952.5	3,174.50
3.0	22,288.01	28,557.90	891.25	3,288.50

By contrast, unmet cooling hours decrease by around 10% at 1.0 ACH and nearly 17% at 2.0 ACH, before falling by roughly 22% at 3.0 ACH compared with the Passivhaus benchmark. Over the same range, ASHRAE 55 discomfort hours rise only modestly, by around 1% at 1.0 ACH, 9% at 2.0 ACH and 13% at 3.0 ACH, pointing to a gradual deterioration in overall comfort

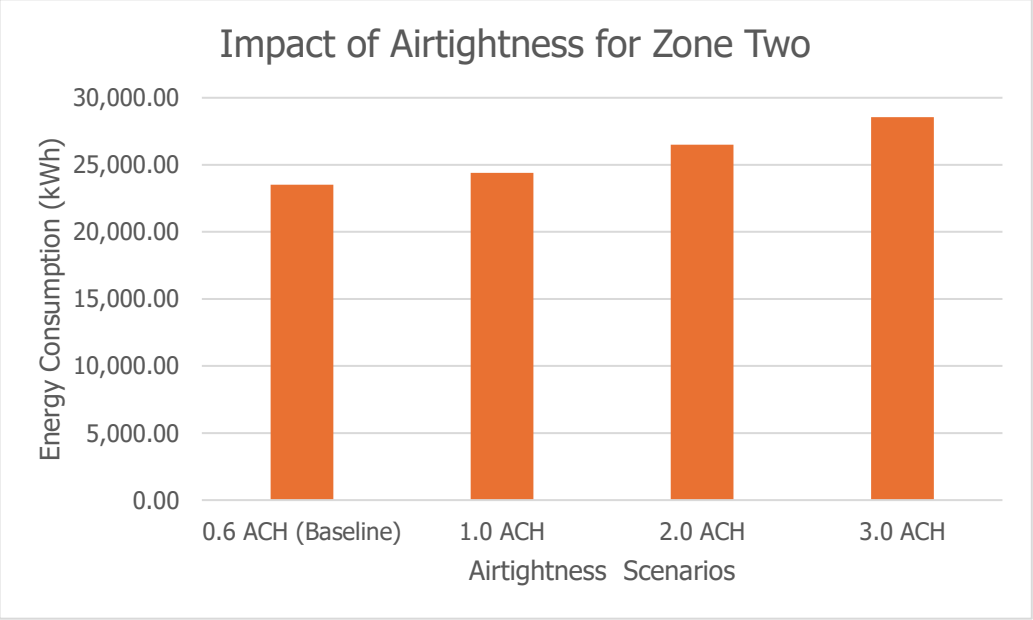


Figure 8.8 Airtightness Impact on Annual Energy Consumption in Riyadh

Figure 8.8, which plots total annual energy consumption against airtightness level for Riyadh, reinforces the numerical trends reported in Table 8.25. The bars show a steady increase in energy use as the infiltration rate is relaxed from the Passivhaus benchmark of 0.6 ACH to 1.0, 2.0 and 3.0 ACH, with the highest leakage level requiring almost one-quarter more energy than the baseline despite the same envelope specification. This visual progression underlines that even moderate departures from the 0.6 ACH target carry a clear energy penalty, supporting the argument that tight construction remains a critical component of high-performance design in Riyadh's hot, dry-continental climate.

Indeed, from a design standpoint, the 1.0 ACH scenario emerges as the most balanced option for Riyadh, since it preserves most of the energy advantage associated with the 0.6 ACH benchmark while delivering a modest reduction in unmet cooling hours and avoiding the substantial energy penalties observed at 2.0–3.0 ACH.

C. Dammam

In Zone Three, the airtightness sensitivity analysis examines how relaxing the infiltration rate from the selected Passivhaus scenario of 0.6 ACH affects the performance of the optimised envelope, with wall and roof U-values held at 0.15 W/m²K and a WWR of 10% under identical climatic and operational conditions. Table 8.26 summarises the variation in energy consumption and thermal comfort across the four airtightness levels, while Figure 8.9 illustrates the corresponding change in annual energy consumption.

Relative to the 0.6 ACH reference case, relaxing airtightness to 1.0 ACH increases cooling energy by about 5% and total site energy by roughly 4%. At 2.0 ACH, cooling demand is higher by around 17% and total energy by approximately 13%, and at 3.0 ACH the increases reach roughly 29% and 22% respectively, indicating a clear and progressive efficiency penalty as the envelope becomes leakier. These trends are evident in Figure 8.9, where total energy use rises almost linearly between 0.6 and 3.0 ACH despite the unchanged envelope specification.

Table 8.26 Airtightness Sensitivity Results for Dammam

Airtightness Scenario (ACH)	Cooling Energy (kWh)	Total Energy (kWh)	Unmet Cooling (hrs)	ASHRAE 55 Discomfort (hrs)
0.6 (Selected PH)	16,975.74	23,031.39	713.75	4,396.25
1.0	17,863.65	23,948.96	656.25	4,450.75
2.0	19,933.89	26,085.85	594	4,570.00
3.0	21,890.48	28,104.07	560	4,681.00

The comfort metrics respond more subtly. Unmet cooling hours fall by about 8% at 1.0 ACH and around 17% at 2.0 ACH, before decreasing by roughly 22% at 3.0 ACH compared with the selected Passivhaus case, suggesting some alleviation of peak cooling shortfalls as infiltration increases. In contrast, ASHRAE 55 discomfort hours rise steadily by approximately 1%, 4% and 6% at 1.0, 2.0 and 3.0 ACH, indicating a gradual deterioration in overall comfort despite the reduction in unmet hours.

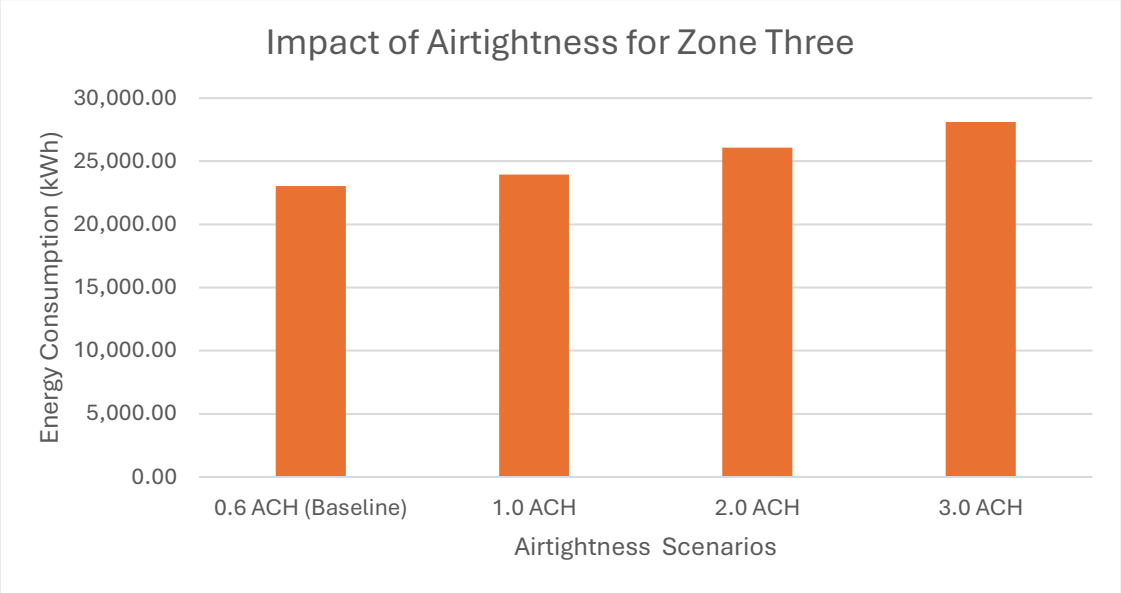


Figure 8.9 Airtightness Impact on Annual Energy Consumption in Dammam

Overall, the Dammam results show that airtightness acts mainly as an energy-efficiency measure in this warm-humid coastal climate: keeping infiltration in the 0.6–1.0 ACH range retains most of the benefit of the optimised envelope, whereas 2.0–3.0 ACH produces substantial increases in cooling demand and total energy for only limited comfort improvement. This indicates that relatively tight construction should remain a priority in Dammam, supported by appropriate ventilation and

moisture-control strategies rather than reliance on uncontrolled infiltration to regulate indoor conditions.

D. Tabuk

In Zone Four, the airtightness sensitivity results in Table 8.27 demonstrate a clear trade-off between energy efficiency and unmet cooling hours as infiltration is relaxed from the selected Passivhaus level of 0.6 ACH to 3.0 ACH. Cooling energy rises by around 3% at 1.0 ACH, 9% at 2.0 ACH and 16% at 3.0 ACH relative to the 0.6 ACH baseline, while total site energy increases by roughly 2%, 8% and 13% across the same sequence, indicating a progressively stronger energy penalty as the building becomes leakier.

Table 8.27 Airtightness Sensitivity Results for Tabuk

Airtightness Scenario (ACH)	Cooling Energy (kWh)	Total Energy (kWh)	Unmet Cooling (hrs)	ASHRAE 55 Discomfort (hrs)
0.6 (Selected PH)	8,986.47	15,713.61	334.25	4,501.75
1.0	9,223.93	16,033.61	171.25	4,518.50
2.0	9,805.79	16,950.13	92	4,592.50
3.0	10,392.17	17,751.13	54.5	4,683.25

In contrast, unmet cooling hours fall by about 49% at 1.0 ACH, 72% at 2.0 ACH and 84% at 3.0 ACH, whereas ASHRAE 55 discomfort hours rise more gently, by approximately 0.4%, 2% and 4% respectively, suggesting that large reductions in peak unmet hours are achieved at the cost of only modest deterioration in overall comfort.

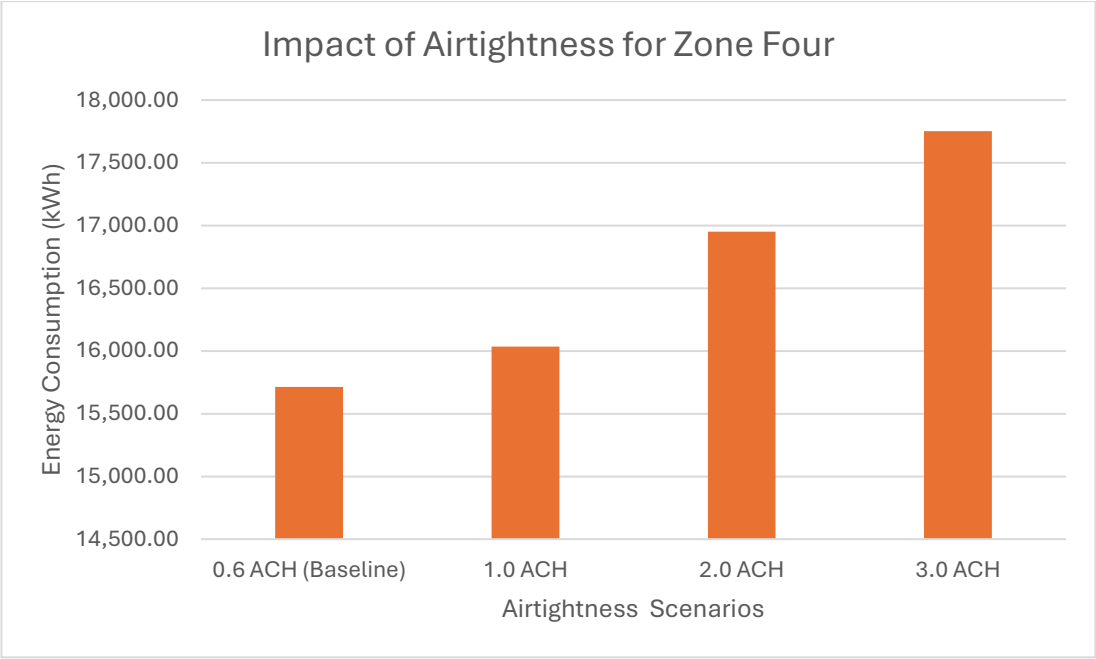


Figure 8.10 Airtightness Impact on Annual Energy Consumption in Tabuk

These patterns are clearly reflected in Figure 8.10, where the bars show a smooth upward trend in annual energy consumption from 0.6 to 3.0 ACH despite the unchanged envelope specification, visually emphasising how relatively small relaxations in airtightness accumulate into noticeable energy penalties. Taken together, the table and the diagram indicate that, in Tabuk's cooler continental climate, loosening airtightness can be justified when reducing unmet cooling hours is prioritised, yet maintaining tighter construction remains important for minimising total energy use.

E. Abha

As illustrated in Table 8.28, the airtightness sensitivity analysis reveals a modest decline in cooling energy as infiltration is relaxed from the selected Passivhaus level of 0.6 ACH to 3.0 ACH, with cooling demand falling by around 3% at 1.0 ACH, 9% at 2.0 ACH and 14% at 3.0 ACH relative to the baseline. Over the same range, total annual site energy increases by approximately 0.1%, 4% and 8%, indicating that any local gains in cooling efficiency are outweighed by higher overall energy use in the leakier configurations.

Table 8.28 Airtightness Sensitivity Results for Abha

Airtightness Scenario (ACH)	Cooling Energy (kWh)	Total Energy (kWh)	Unmet Cooling (hrs)	ASHRAE 55 Discomfort (hrs)
0.6 (Selected PH)	1,593.65	7,754.60	43	4,905.75
1.0	1,541.32	7,759.33	29.25	4,895.00
2.0	1,451.31	8,032.92	20	5,117.75
3.0	1,373.37	8,392.36	16.25	5,297.50

Comfort-related indicators follow a different pattern. Unmet cooling hours drop sharply, by about 32% at 1.0 ACH, 53% at 2.0 ACH and 62% at 3.0 ACH, demonstrating that relaxing airtightness substantially reduces the frequency of hours when the system cannot meet the cooling set-point.

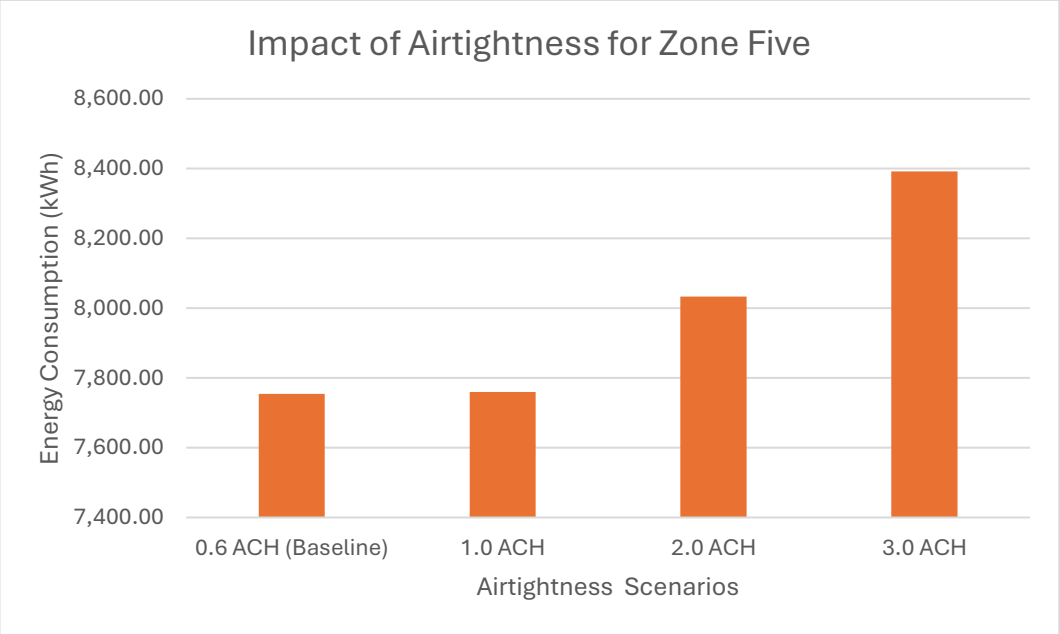


Figure 8.11 Airtightness Impact on Annual Energy Consumption in Abha

However, ASHRAE 55 discomfort hours rise steadily, by roughly 0.2%, 4% and 8% across the same progression, suggesting that the reduction in peak unmet hours is achieved at the expense of slightly more time spent outside the comfort envelope.

These interactions are clearly reflected in Figure 8.11, where the bars display a smooth upward trend in annual energy consumption from 0.6 to 3.0 ACH despite the unchanged envelope specification, visually emphasising how incremental relaxations in airtightness accumulate into noticeable energy penalties. Taken together, Figure

8.11 and Table 8.28 indicate that, in Abha's cooler highland climate, some relaxation from the strict 0.6 ACH Passivhaus target may be justified if reducing unmet cooling hours is prioritised, but maintaining relatively tight construction remains important to preserve the substantial energy savings achieved by the optimised envelope. In this context, the selected scenario of 1.0 ACH therefore offers a practical balance between energy consumption and thermal comfort.

In conclusion, across all five zones, the airtightness sensitivity analysis demonstrates that relaxing from the Passivhaus target of 0.6 ACH consistently reduces unmet cooling hours but gradually increases annual energy consumption and ASHRAE 55 discomfort hours. The results therefore indicate that moderately relaxed airtightness levels (typically around 1.0–2.0 ACH, depending on climate) can offer a pragmatic balance between energy performance and thermal comfort, whereas higher leakage rates (3.0 ACH) erode much of the benefit provided by the optimised envelopes.

8.5 The Adapted Passivhaus Framework

The Adapted Passivhaus framework proposed in this thesis is conceptualised as a climate-responsive bridge between the stringent, European-centric parameters of the classic Passivhaus standard (PHI) and the baseline regulatory requirements of the Saudi Building Code (SBC). While the SBC provides a foundational level of thermal performance for the Saudi context, and the classic Passivhaus offers a rigorous standard for maximum energy efficiency, neither is entirely optimal for the distinct climatic variations across the Kingdom. Therefore, the Adapted Passivhaus framework is defined as a calibrated set of building fabric and energy performance criteria that systematically relaxes or modifies specific PHI constraints, most notably space cooling demands and insulation thresholds, to achieve pragmatic, low-energy residential performance tailored specifically to the realities of Saudi Arabia's five distinct climate zones.

To clearly articulate this relationship, Table 8.29 presents a comparative matrix. It illustrates how the proposed adapted parameters contrast with both the existing national regulations (SBC) and the original Passivhaus limits.

Table 8.29 Comparison of Building Performance Parameters

Parameter/Code	SBC Zone 1	SBC Zone 2	SBC Zone 3	Passivhaus	Adapted: Zone 1	Adapted: Zone 2	Adapted: Zone 3	Adapted: Zone 4	Adapted: Zone 5
Wall U-value (W/m^2K)	0.342	0.397	0.453	≤ 0.15	≤ 0.15	≤ 0.15	≤ 0.20	≤ 0.20	≤ 0.30
Roof U-value (W/m^2K)	0.202	0.238	0.273	≤ 0.15	≤ 0.15	≤ 0.15	≤ 0.20	≤ 0.20	≤ 0.30
Glazing U-value (W/m^2K)	≤ 2.668	≤ 2.668	≤ 2.668	≤ 0.80	≤ 0.80	≤ 0.80	≤ 0.80	≤ 0.80	≤ 0.80
Airtightness (n50)	≤ 4.0 ACH	≤ 4.0 ACH	≤ 4.0 ACH	≤ 0.6 ACH	≤ 1.0 ACH	≤ 1.0 ACH	≤ 1.0 ACH	≤ 1.0 ACH	≤ 1.0 ACH
WWR %	≤ 25%	≤ 25%	≤ 25%	N/A	≤10%	≤10%	≤10%	≤12%	≤10%

*Note: SBC climate zones correspond to the adapted zones as follows: SBC Zone 1 includes Adapted Zones 1, 2, and 3; SBC Zone 2 includes Adapted Zone 4; and SBC Zone 3 includes Adapted Zone 5.

8.6 Summary

The Passivhaus standard is a viable framework for application in Saudi Arabia; however, it necessitates contextual adaptations that prioritise cooling efficiency, hybrid ventilation approaches, and the effective integration of solar energy systems. Although achieving full certification may not always be feasible, the underlying principles of Passivhaus offer a robust foundation for the development of high-performance, low-energy buildings aligned with the sustainability objectives of the Saudi Vision 2030.

9 CONCLUSIONS

This chapter concludes the investigation into the applicability of the Passivhaus standard to Saudi residential buildings across five representative climatic zones. Using a validated baseline model, adapted to comply with both the Saudi Building Code (SBC) and Passivhaus criteria, the study evaluates the comparative performance of these frameworks in each zone. The chapter highlights the opportunities and challenges of implementing Passivhaus principles under Saudi climatic conditions, synthesises the primary research findings, and outlines the study's contribution to knowledge. Finally, it acknowledges the limitations of the research and proposes directions for future work.

9.1 Research Findings

The study confirmed that Saudi residential buildings are highly energy-intensive, dominated by space cooling across all climates. Multi-year cooling degree days refined climatic zoning, establishing Madinah, Riyadh, Dammam, Tabuk, and Abha as representatives of five distinct zones with differentiated cooling demands.

Calibrated baseline models revealed climate-dependent electricity use and energy use intensity (EUI), with cooling comprising over 80% of consumption everywhere and heating negligible. Madinah showed the highest annual energy consumption (37,015.26 kWh/year), followed by Riyadh, Dammam, and Tabuk, whilst Abha demonstrated the lowest (25,754.19 kWh/year), confirming a severity hierarchy. Saudi Building Code (SBC) compliance yielded modest reductions 16-37% in total electricity but cooling dominated end-use profiles. Passivhaus scenarios delivered the greatest savings about 25-70% in annual energy vs. baseline, while sustaining thermal comfort. Full compliance proved challenging in hotter zones (Madinah, Riyadh, Dammam, Tabuk) due to cooling focus over heating benchmarks, but feasible in Abha.

Parametric analyses identified zone-specific optima for key envelope parameters. Modest window-to-wall ratios (10-15%) on exposed façades balanced cooling demand and thermal comfort across all zones. U-values of 0.15-0.30 W/m²K for walls and roofs maximised energy gains with diminishing returns beyond, while airtightness <0.6 ACH minimised use, though 1.0-2.0 ACH better balanced performance and constructability.

The findings directly address the five research questions outlined in Chapter 1 as follows, demonstrating Passivhaus feasibility and required adaptations for Saudi Arabia's cooling-dominated climates.

1. What are the key international requirements and performance criteria of the Passivhaus standard for residential buildings?

The study showed that the Passivhaus standard is defined internationally by quantitative performance criteria, including very low annual space-conditioning demand, strict limits on primary energy use and a high level of airtightness, supported by qualitative design principles such as super-insulation, thermal-bridge-free detailing, high-performance windows and mechanical ventilation with heat recovery. These requirements form the benchmark against which the Saudi case studies were evaluated and highlight the gap between conventional practice and best-practice low-energy housing.

2. What is the current energy performance of residential buildings in Saudi Arabia, particularly in terms of annual electricity consumption?

Analysis of the calibrated baseline model across the five representative cities demonstrated that current Saudi residential buildings are highly energy-intensive, with annual electricity consumption for the typical flat ranging from 23,842.79 kWh in the mildest climates to 37015 kWh in the most demanding. Cooling accounted for most of this use in every location, while heating demand was effectively negligible, confirming that Saudi homes operate under a consistently cooling-dominated regime.

3. To what extent have Passivhaus principles been adopted in the Saudi residential construction sector?

The review of the Saudi residential sector and case-study building confirmed that Passivhaus principles have not been adopted. Pre-SBC construction typically featured uninsulated concrete block walls, single glazing, and natural ventilation with poor envelope performance. Although SBC implementation has established minimum standards and delivered modest energy improvements, these remain basic requirements far short of Passivhaus principles of super-insulation, airtightness, and mechanical ventilation.

4. What are the expected impacts of adopting the Passivhaus standard in Saudi residential buildings?

Th Passivhaus scenarios consistently achieved the largest reductions in annual energy consumption and energy use intensity compared with both baseline and SBC-compliant models, while maintaining or improving thermal comfort across all five climatic zones. These results confirm that applying Passivhaus principles to Saudi residential buildings has the potential to deliver substantial reductions in electricity demand, particularly for cooling, beyond those achievable through current code requirements alone.

5. Are the existing Passivhaus standard for hot climates applicable in Saudi Arabia, or do they require adaptation to local climatic and regulatory conditions?

The findings indicate that the existing Passivhaus criteria, developed primarily for Central European climates, are only partially applicable in Saudi Arabia and require adaptation. In particular, the space-heating demand benchmark is not meaningful in climates where heating is negligible, and strict adherence to all criteria proved challenging in the hotter zones of Madinah, Riyadh, Dammam, and to a lesser extent Tabuk, whereas performance in Abha aligned more closely with full Passivhaus expectations.

9.2 Recommendations

Based on these integrated findings, the thesis recommends that any Saudi adaptation of Passivhaus should retain the standard's fundamental principles, a high-performance envelope with reduced thermal bridging, high-quality glazing, airtight construction and mechanical ventilation with heat recovery, while redefining performance criteria in terms of cooling demand, primary energy use and indoor comfort rather than heating energy. The optimised window-to-wall ratios, wall and roof U-values and airtightness levels derived for each climatic zone can serve as initial benchmarks for a Saudi-specific Passivhaus framework and as evidence-based targets for future revisions of the Saudi Building Code.

More broadly, the research underlines the importance of climate-sensitive design within national regulations, arguing that more differentiated zoning and explicit performance metrics for cooling-dominated buildings would better reflect actual

energy and comfort needs across the Kingdom of Saudi Arabia. Passivhaus-inspired designs across all zones indicate that, when appropriately configured, they can achieve substantial reductions in energy consumption compared with both current practices, represented by the baseline models, and the improved performance mandated by the SBC.

The most effective approach for the Saudi residential sector is therefore to revise the current SBC by integrating Passivhaus principles, creating a Saudi-specific high-performance standard that maintains strong energy-saving potential while responding to local climatic conditions. In parallel, it is recommended that the Passivhaus Institute develops a dedicated standard for hot and arid countries, reflecting the specific physics of cooling-dominated environments and the practical challenges of applying the current Central European model in extreme heat. Such a standard should prioritise limits on cooling demand, primary energy use and indoor comfort over heating metrics and provide greater flexibility in total allowable cooling demand.

9.3 Contribution to knowledge

The thesis makes several contributions to knowledge on building energy performance and sustainable housing in hot and dry countries such as the Kingdom of Saudi Arabia. It develops a refined climatic zoning for the Kingdom based on multi-year cooling degree days, explicitly linked to residential cooling demand, and validates five representative zones for detailed simulation. This zoning framework provides a performance-oriented basis for regulatory and design decisions, moving beyond classifications that are weakly related to building energy use.

The research also produces a calibrated, transferable residential building model that is applied consistently across multiple climatic zones, enabling systematic comparison of baseline, SBC-compliant and Passivhaus scenarios. Coupled with parametric optimisation of key Passivhaus parameters, window-to-wall ratios, wall and roof U-values and airtightness, the work generates climate-specific guidance directly relevant to architects, engineers and policymakers in Saudi Arabia and other cooling-dominated regions. In doing so, the thesis provides a comprehensive, simulation-based evaluation of Passivhaus feasibility and adaptation across the full range of Saudi climates, demonstrating both the potential energy and comfort benefits and the need for tailored performance criteria.

9.4 Challenges and limitations

Several challenges and limitations should be acknowledged when interpreting the findings of this thesis. The calibration of the baseline model relied on monthly electricity bills, although adequate for establishing overall accuracy, does not capture day-to-day variability or allow individual end-uses to be disaggregated. In addition, the use of identical occupancy schedules and internal gains for all five cities simplifies reality and may obscure regional or cultural differences in household behaviour and appliance use.

The study also did not address the economic, institutional and supply-chain dimensions of implementing Passivhaus or Passivhaus-inspired standards in Saudi Arabia, including issues such as installer training, material availability and regulatory enforcement, even though these factors are likely to strongly influence real-world uptake. Despite these limitations, the thesis offers a robust, evidence-based assessment of Passivhaus applicability across Saudi climatic zones and proposes a structured pathway for adapting the standard to local conditions, thereby providing a foundation for future research and policy development.

9.5 Future work

First, analysis should be extended to a wider range of dwelling types and layouts, such as detached houses (villas) and mixed-use developments, for example by examining representative flat and villa designs from Saudi national housing programmes such as the Sakani projects delivered by the National Housing Company.

Second, future studies should employ different building-performance tools, such as PHPP, and support these with higher-frequency monitored data for indoor temperature, humidity, energy use to enable more robust validation. The integration of on-site renewable energy systems, particularly photovoltaic upgrades, with optimised envelopes also warrants further study, including the potential for net-zero or net-positive energy housing and its implications for grid demand.

Finally, future doctoral research could focus on humid coastal cities in the west, east, south and north of the Kingdom, such as Jeddah, Yanbu, Umluj, Jizan, Dhahran, Neom, Al-Wajh and Duba, to evaluate how Passivhaus-based strategies perform in marine and humid climates compared with inland locations.

REFERENCES

Abu Bakar, N. N., M. Y. Hassan, H. Abdullah, H. A. Rahman, M. P. Abdullah, F. Hussin and M. Bandi (2015). "Energy efficiency index as an indicator for measuring building energy performance: A review." Renewable and Sustainable Energy Reviews **44**: 1-11.

Abuhussain, M. (2020). An assessment of the Saudi Residential Buildings Envelope Code under the current and future climate change scenarios: the case for Jeddah in the hot and humid climate region, University of Liverpool.

Ahmed, W., M. Asif and F. Alrashed (2019). "Application of Building Performance Simulation to Design Energy-Efficient Homes: Case Study from Saudi Arabia." Sustainability **11**(21): 6048.

Akinsooto, O., D. De Canha and J. Pretorius (2014). Energy savings reporting and uncertainty in Measurement & Verification. 2014 Australasian Universities Power Engineering Conference (AUPEC), IEEE.

Al-Abduljabbar, A., M. Al-Mogbel, S. N. Danish and A. El-Leathy (2023). "Insulation Performance of Building Components and Effect on the Cooling Load of Homes in Saudi Arabia." Sustainability **15**(7): 5685.

Al-Hadhrami, L. (2013). "Comprehensive review of cooling and heating degree days characteristics over Kingdom of Saudi Arabia." Renewable and sustainable energy reviews **27**: 305-314.

Al-Homoud, M. S. (1998). "Variable-base heating and cooling degree-day data for 24 Saudi Arabian cities." ASHRAE transactions **104**: 320.

Al-Saadi, S., G. Al-Rawas, L. Gunawardhana, N. Al-Farsi and H. Al-Kalbani (2022). "Developing Climate Classification for Oman Using Degree-Days Method." Arabian Journal for Science and Engineering: 1-15.

Al-Sanea, S. A., M. F. Zedan, A. M. Al-Mujahid and Z. A. Al-Suhaibani (2016). "Optimum R-values of building walls under different climatic conditions in the Kingdom of Saudi Arabia." Applied Thermal Engineering **96**: 92-106.

Al-Tamimi, N. (2017). "A state-of-the-art review of the sustainability and energy efficiency of buildings in Saudi Arabia." Energy Efficiency **10**(5): 1129-1141.

Al-Tamimi, N. (2021). "An Optimum Thermal Insulation Type and Thickness for Residential Buildings in Three Different Climatic Regions of Saudi Arabia." Civil Engineering and Architecture **9**(2): 317-327.

Al Surf, M. (2014). CHALLENGES FACING THE APPLICATION OF SUSTAINABILITY TO HOUSING IN SAUDI ARABIA. Doctor of Philosophy PhD, Queensland University of Technology.

Al Surf, M., A. Balabel, M. Alwetaishi, A. Abdelhafiz, U. Issa, I. Sharaky, A. Shamseldin and M. Al-Harthi (2021). "Stakeholder's Perspective on Green Building Rating Systems in Saudi Arabia: The Case of LEED, Mostadam, and the SDGs." Sustainability **13**(15): 8463.

Al Surf, M., C. Susilawati and B. Trigunarsyah (2013). "Integration of Saudi Arabia's conservative Islamic culture in sustainable."

Al Surf, M., C. Susilawati and B. Trigunarsyah (2014). CASE STUDY ANALYSIS FOR THE DEVELOPMENT AND IMPLEMENTATION OF SUSTAINABLE HOUSING IN THE KINGDOM OF SAUDI ARABIA.

Al Surf, M., C. Susilawati and B. Trigunarsyah (2014). Case study analysis for the development and implementation of sustainable housing in the Kingdom of Saudi Arabia. The Asian Real Estate Society 19th Annual Conference, Asian Real Estate Society.

Alaidroos, A. and M. Krarti (2015). "Optimal design of residential building envelope systems in the Kingdom of Saudi Arabia." Energy and Buildings **86**: 104-117.

Alaidroos, A. and M. Krarti (2016). "Evaluation of Passive Cooling Systems for Residential Buildings in the Kingdom of Saudi Arabia."

Alalouch, C., M. S.-E. Saleh and S. Al-Saadi (2016). "Energy-Efficient House in the GCC Region." Procedia - Social and Behavioral Sciences **216**: 736-743.

Alardhi, A., A. S Alaboodi and R. Almasri (2022). "Impact of the new Saudi energy conservation code on Saudi Arabia residential buildings." Australian Journal of Mechanical Engineering **20**(5): 1392-1406.

Alayed, E., R. O'hegarty and O. Kinnane (2021). "Thermal envelope analysis for new code compliance of Saudi Arabian dwellings." Energy and Buildings **243**: 110997.

AlGhamdi, A. (2020). Saudi Arabia Energy Report, King Abdullah Petroleum Studies and Research Center.

Alosaimi, A. (2023). Optimising the energy performance of the residential stock of the Kingdom of Saudi Arabia by retrofit measures, University of Nottingham (United Kingdom).

Alrashed, F. and M. Asif (2012). Challenges facing the application of zero-energy homes in Saudi Arabia: Construction industry and user perspective. Proceedings of the ZEMCH 2012 International Conference, Glasgow, UK.

Alrashed, F. and M. Asif (2014). "Analysis of critical climate related factors for the application of zero-energy homes in Saudi Arabia." Renewable and Sustainable Energy Reviews **41**: 1395-1403.

Alrashed, F. and M. Asif (2015). "Climatic Classifications of Saudi Arabia for Building Energy Modelling." Energy Procedia **75**: 1425-1430.

Alshahrani, J. (2018). "Smart Solutions to Manage Peak Electricity Demand in Saudi Arabia."

Alshaikh, A. M. A. (2016). "Design Principles for Thermally Comfortable and Low Energy Homes in the Extreme Hot-Humid Climatic Gulf Region, with reference to Dammam, Saudi Arabia." 268.

Alshehri, T., N. Howarth, R. Fuentes and N. Odnoletkova (2020). "The Future of Cooling in Saudi Arabia: Technology, Market and Policy Options."

Alshenaif, M. (2015). High performance homes in Saudi Arabia Revised Passivhaus principles for hot and arid climates, M. Sc. Thesis, Philadelphia University.

Alulayet, M., K. Panuwatwanich, R. Hyde and F. Fiorito (2012). The evolution of a framework for Building Environmental Assessment (BEA) for green buildings in Saudi Arabia. 46th Annual Conference of the Architectural Science Association.

Aluwaisheg, A. A. (2013). "High stakes of energy conservation in Saudi Arabia." Arab News.

Alwetaishi, M. (2019). "Impact of glazing to wall ratio in various climatic regions: A case study." Journal of King Saud University-Engineering Sciences **31**(1): 6-18.

Alyami, M. (2022). An approach to enhancing energy performance in residential buildings in hot climate regions (The case of Saudi Arabia) PhD, University of Nottingham.

Amin, M., S. Mahmoud and A. Alazba (2016). "Observations, projections and impacts of climate change on water resources in Arabian Peninsula: current and future scenarios." Environmental Earth Sciences **75**(10): 1-17.

Anderson, C. (2010). "Presenting and Evaluating Qualitative Research." American Journal of Pharmaceutical Education **74**(8): 141.

ASHRAE (2014). "Measurement of energy, demand, and water savings." ASHRAE guidel **4**: 1-150.

Balabel, A. and M. Alwetaishi (2021). "Towards Sustainable Residential Buildings in Saudi Arabia According to the Conceptual Framework of “Mostadam” Rating System and Vision 2030." Sustainability **13**(2): 793.

Beck, H. E., N. E. Zimmermann, T. R. Mcvicar, N. Vergopolan, A. Berg and E. F. Wood (2018). "Present and future Köppen-Geiger climate classification maps at 1-km resolution." Scientific Data **5**(1): 180214.

Benali, L. R., M. Ansari and R. Al-Ashmaw (2020). MENA Power Investment Outlook 2020-2024. APICORP.

BizEE Software. (2022). "Calculating Degree Days." from https://www.degreedays.net/calculation.

BizEE Software. (2022). "Degree Days Calculated Accurately for Locations Worldwide." Retrieved 04/23/2022, from https://www.degreedays.net/.

Büyükalaca, O., H. Bulut and T. Yılmaz (2001). "Analysis of variable-base heating and cooling degree-days for Turkey." Applied Energy **69**(4): 269-283.

Cainthus (2020). "The Sustainability Triangle of Truth."

Causone, F., M. Pietrobon, L. Pagliano and S. Erba (2017). "A high performance home in the Mediterranean climate: from the design principle to actual measurements." Energy Procedia **140**: 67-79.

CIBSE, T. (2006). "Degree-days: theory and application." London: The Chartered Institution of Building Services Engineers **16**.

Cowan, J. (2002). "International performance measurement and verification protocol: Concepts and Options for Determining Energy and Water Savings-Vol. I." International Performance Measurement & Verification Protocol **1**.

Creswell, J. W. (2014). The selection of a research approach. Research design: Qualitative, quantitative, and mixed methods approaches, SAGE Publications**:** 3-24.

Cui, Y., Z. Zhu, X. Zhao, Z. Li and P. Qin (2022). "Bayesian calibration for office-building heating and cooling energy prediction model." Buildings **12**(7): 1052.

Dahish, H. A., S. Almutairi, A. F. Elragi and S. M. ElKholy (2020). "Interactive and Educative Software for Designing Concrete Mixtures Utilizing Saudi Building Code." JOURNAL OF ENGINEERING AND COMPUTER SCIENCES **13**(2): 16-44.

Dequaire, X. (2012). "Passivhaus as a low-energy building standard: contribution to a typology." Energy Efficiency **5**(3): 377-391.

Echarri-Iribarren, V., C. Sotos-Solano, A. Espinosa-Fernández and R. Prado-Govea (2019). "The Passivhaus Standard in the Spanish Mediterranean: Evaluation of a House's Thermal Behaviour of Enclosures and Airtightness." Sustainability **11**(13): 3732.

ECRA (2019). "Annual Statistical Booklet for Electricity & Seawater Desalination Industries." Electricity & Cogeneration Regulatory Authority, KSA.

EIC (2019). "Saudi Arabia country report summary."

Energy House 2.0. (2023). "Energy House Labs." Retrieved 24/07/2023, from https://energyhouse2.salford.ac.uk/energy-house-labs/.

Energy Plus Project (2016). "Office Building certified to Passivhaus Standard in UAE."

Fahy, M. (2013). "Site visit: Baytna project in Barwa City, Qatar." Construction Week Middle East, from https://www.constructionweekonline.com/projects-tenders/article-24193-site-visit-baytna-project-barwa-city.

Feist, W. (2006). "Definition of Passive Houses." Passive House Institute, from https://passiv.de/former_conferences/Passive_House_E/passivehouse_definition.html.

Feist, W. (2015). 25 Years of Passive House - Interview with Dr. Wolfgang Feist. K. Krämer, PHI.

Feist, W., R. Pfluger and W. Hasper (2020). "Durability of building fabric components and ventilation systems in passive houses." Energy Efficiency **13**(8): 1543-1559.

Felimban, A. (2024). "Towards Energy-Efficient Residential Buildings In Jeddah, Saudi Arabia: Exploring Energy Retrofitting Options And Assessing Their Feasibility."

free world maps. (2021). "Saudi Arabia Physical Map." Free World Maps, from http://www.freeworldmaps.net/asia/saudiarabia/map.html.

GAStat (2020). GASTAT Statistical Database. General Authority for statistics.

Ghabra, N. (2018). Energy efficient strategies for the building envelope of residential tall buildings in Saudi Arabia. PhD, University of Nottingham.

Harvey, L. D. (2020). "Using modified multiple heating-degree-day (HDD) and cooling-degree-day (CDD) indices to estimate building heating and cooling loads." Energy and Buildings **229**: 110475.

Hasanean, H. and M. Almazroui (2015). "Rainfall: Features and Variations over Saudi Arabia, A Review." Climate **3**(3): 578-626.

Hines, J., Sally Godber, Bill Butcher, Mark Siddall, Paul Jennings, Nick Grant, Alan Clarke, Kym Mead and C. Parsons (2015). How to build a Passivhaus: Rules of thumb. Passivhaus Trust, Passivhaus Trust.

iPHA. (2016). "Passive House certification criteria." Retrieved 18/05/2022, from https://passivehouse-international.org/index.php?page_id=150.

iPHA (2021). Passive House now 30 years old, Passive House Institute.

iPHA. (2022). "The global Passive House platform." from https://passivehouse-international.org/index.php?page_id=65.

JLL (2022). The KSA Real Estate Market. JONES LANG LASALLE.

Kang, Y., V. W.-C. Chang, D. Chen, V. Graham and J. Zhou (2021). "Performance gap in a multi-storey student accommodation complex built to Passivhaus standard." Building and Environment **194**: 107704.

Khalfan, M. (2017). AN ASSESSMENT OF THE PASSIVHAUS STANDARD FOR A HOT AND ARID CLIMATE: A CASE STUDY IN QATAR. Doctor of Philosophy (PhD), University of Liverpool.

Khalfan, M. (2019). "Lessons Learned from the First Passivhaus Building in Qatar." International Journal of Environmental Science & Sustainable Development **4**(3): 77-91.

Khalfan, M. and S. Sharples (2016). "The Present and Future Energy Performance of the First Passivhaus Project in the Gulf Region." Sustainability **8**(2): 139.

Khalfan, M., S. Sharples, A. Amato, C. Skelhorn and J. Bryant (2015). "The first Passivhaus in Qatar: initial monitoring and modelling energy performance."

Krämer, K. (2020). Passive House buildings lead the way, Passive House Institute,.

Krarti, M., M. Aldubyan and E. Williams (2020). "Residential building stock model for evaluating energy retrofit programs in Saudi Arabia." Energy **195**: 116980.

Krarti, M. and P. Ihm (2016). "Evaluation of net-zero energy residential buildings in the MENA region." Sustainable cities and society **22**: 116-125.

Ladybug Tools Academy. (nd). "Climate Zone Classification." from https://docs.ladybug.tools/ladybug-tools-academy/v/climate-analysis/climate-zone-classification.

Landreneau, A. (2014). "With End of Oil in Sight, Saudi Arabia's LEED Community is Vision of Sustainable Future." SGBF.

Lasker, W. J. A. (2016). The impact of construction and building materials on energy consumption on Saudi residential buildings, Heriot-Watt University.

Lee, K., H.-J. Baek and C. Cho (2014). "The Estimation of Base Temperature for Heating and Cooling Degree-Days for South Korea." Journal of Applied Meteorology and Climatology **53**(2): 300-309.

Liu, C. (2021). Evaluating Passivhaus EnerPHit Retrofit Strategies for Low-Rise Suburban Dwellings in China's Hot Summer-Cold Winter Climate Region PhD, School of Architecture, University of Liverpool.

Liu, C., S. Sharples and H. Mohammadpourkarbasi (2021). "Evaluating Insulation, Glazing and Airtightness Options for Passivhaus EnerPHit Retrofitting of a Dwelling in China's Hot Summer–Cold Winter Climate Region." Energies **14**(21): 6950.

Lynch, H. (2014). Passivhaus in the UK: the challenges of an emerging market. A case study of innovation using mixed methods research, UCL (University College London).

McLeod, R., M. Jaggs, B. Cheeseman, A. Tilford and K. Mead (2014). "Passivhaus primer: Airtightness Guide, Airtightness and air pressure testing in accordance with the Passivhaus Standard." BRE Trust.

meteoblue. (2023). "Simulated Historical Climate and Weather Data."

Mitchell, R. and S. Natarajan (2020). "UK Passivhaus and the energy performance gap." Energy and Buildings **224**: 110240.

Moreno-Rangel, A. (2020). "Passivhaus." Encyclopedia **1**(1): 20-29.

Mujeebu, M. A. and O. S. Alshamrani (2016). "Prospects of energy conservation and management in buildings–The Saudi Arabian scenario versus global trends." Renewable and Sustainable Energy Reviews **58**: 1647-1663.

Parry, C. (2014). "Passivhaus in Australia." Environment **1**.

Passive House Institute (2019). Two Residential Passive House Towers in Tianjin Eco-City.

Passivhaus Trust. (2021). "What is Passivhaus?" Passivhaus Trust Retrieved 16/05/2022, from https://www.passivhaustrust.org.uk/what_is_passivhaus.php.

PEDRANTI, R. (2016). "Passive House." from https://richardpedranti.com/passivehouse/.

PHI. (2015). "Passive House requirements." Retrieved 10/05/2022, from https://passiv.de/en/02_informations/02_passive-house-requirements/02_passive-house-requirements.htm.

PHI (2016) "Criteria for the Passive House." old, version 9.

PHI (2018). "Active for more comfort: Passive House." International Passive House Association (iPHA).

PHI. (2021). "Passive House Planning Package (PHPP)." Retrieved 16/05/2022, from https://passiv.de/en/04_phpp/04_phpp.htm.

PHI. (2021). "The Passive House Resource- Basics." Retrieved 16/05/2022, from https://passipedia.org/basics.

PHI. (2021). "The Passive House Resource, Certification." Passipedia Retrieved 17/05/2022, from https://passipedia.org/certification.

PHI (2022). Criteria for the Passive House, EnerPHit and PHI Low Energy Building Standard.

PHI (2023). Criteria for Buildings: Passive House—EnerPHit—PHI Low Energy Building, Passive House Institute Darmstadt, Germany.

PHP (2021). Passive House Turns 30. Passive House Plus, Passive House Plus.

Rasooldeen, M. (2013). Green buildings concept growing. Arab News. **2022**.

Ritchie, H., M. Roser and P. Rosado (2020). Energy. Our World in Data, Our World in Data.

Ruiz, G. and C. Bandera (2017). "Validation of Calibrated Energy Models: Common Errors." Energies **10**(10): 1587.

Said, S.-A. M. (1992). Degree-day base temperature for residential building energy prediction in Saudi Arabia. ASHRAE Winter Meeting, Anaheim, CA, USA, 01/25-29/92.

Said, S.-A. M., H. M. Kadry and B. I. Ismail (1996). Climatic conditions for Saudi Arabia. ASHRAE Winter Meeting.

Said, S. A. M., M. A. Habib and M. O. Iqbal (2003). "Database for building energy prediction in Saudi Arabia." Energy conversion and management **44**(1): 191-201.

Saldaña-Márquez, H., J. Gómez-Soberón, S. P. Arredondo-Rea, J. L. Almaral-Sánchez, M. C. Gómez-Soberón and G. Rosell-Balada (2015). "The passivhaus standard in the mediterranean climate: Evaluation, comparison and profitability." Journal of green building **10**(4): 55-72.

Saudi Ministry of Media (2020) "Geography of Saudi Arabia."

Saudi Vision 2030 (2021). The Housing Program Delivery Plan (2021-2025), Saudi Arabia Government.

SBC 602 (2018). "602 Residential Buildings - Energy Conservation Code." Saudi Building Code National Committee.

SBCNC (2007). "Saudi Building Code (SBC)."

Schnieders, J., W. Feist and L. Rongen (2015). "Passive Houses for different climate zones." Energy and Buildings **105**: 71-87.

Schwartz, E. K. and M. Krarti (2022). "Review of Adoption Status of Sustainable Energy Technologies in the US Residential Building Sector." Energies **15**(6): 2027.

SEC (2021). SEC At Glance. Saudi Electricity Company. 15/02/2022.

SEEC (2021). "Buildings sector."

Soummane, S. and F. Ghersi (2021). "Projecting Saudi Sectoral Electricity Demand in 2030 Using a Computable General Equilibrium Model." KAPSRC.

Susilawati, C. and M. Al Surf (2011). Challenges facing sustainable housing in Saudi Arabia: a current study showing the level of public awareness. Proceedings of the 17th Annual Pacific Rim Real Estate Society Conference, Pacific Rim Real Estate Society.

Taleb, H. M. (2012). Towards sustainable residential buildings in the kingdom of Saudi Arabia phd, University of Sheffield.

U.S. EIA (2021). Saudi Arabia Energy Profile: Maintains World's Largest Crude Oil Production Capacity – Analysis, Eurasia Review.

UK Met Office. (2022). "Climate Zones ", from https://www.metoffice.gov.uk/.

Verfasser der (2016). Passivhaus Office building in UAE. Passivhaus Institut. https://database.passivehouse.com, Passivhaus Institut.

Vettorazzi, E., A. Figueiredo, F. Rebelo, R. Vicente and E. Grala Da Cunha (2021). "Optimization of the passive house concept for residential buildings in the South-Brazilian region." Energy and Buildings **240**: 110871.

Walsh, A., D. Cóstola and L. C. Labaki (2017). "Review of methods for climatic zoning for building energy efficiency programs." Building and Environment **112**: 337-350.

Wang, Y., J. Kuckelkorn, F.-Y. Zhao, H. Spliethoff and W. Lang (2017). "A state of art of review on interactions between energy performance and indoor environment quality in Passive House buildings." Renewable and Sustainable Energy Reviews **72**: 1303-1319.

Warty, A. and S. Mehendale (2021). "Energy Modeling and Energy Efficiency Opportunities for a Public Library Building in the Upper Peninsula of Michigan."

weather&climate (2023). "Climate in Saudi Arabia."

WERA (2020). "Annual Statistical Booklet for Electricity 2020." Water & Electricity Regulatory Authority in KSA.

Williams, C. (2011). "Research Methods." Journal of Business & Economics Research (JBER) **5**(3).

World Bank (2021). Saudi Arabia.

APPENDIX

Appendix A

Table 1 Passive House Criteria

			Criteria[1]			Alternative Criteria[2]
Heating						
Heating demand	[kWh/(m²a)]	≤	15			-
Heating load[3]	[W/m²]	≤	-			10
Cooling						
Cooling + dehumidification demand	[kWh/(m²a)]	≤	15 + dehumidification contribution[4]			variable limit value[5]
Cooling load[6]	[W/m²]	≤	-			10
Airtightness						
Pressurization test result n_{50}	[1/h]	≤	0.6			
Renewable Primary Energy (PER)[7]			Classic	Plus	Premium	
PER demand[8]	[kWh/(m²a)]	≤	60	45	30	±15 kWh/(m²a) deviation from criteria...
Renewable energy generation[9] (with reference to projected building footprint)	[kWh/(m²a)]	≥	-	60	120	...with compensation of the above deviation by different amount of generation

[1] The criteria and alternative criteria apply for all climates worldwide. The reference area for all limit values is the treated floor area (TFA) calculated according to the latest version of the PHPP Manual (exceptions: generation of renewable energy with reference to projected building footprint and airtightness with reference to the net air volume).

[2] Two alternative criteria which are enclosed by a double line together may replace both of the adjacent criteria on the left which are also enclosed by a double line.

Figure 0.1. Passivhaus principles source:(PHI 2016)

2.3 PHI Low Energy Building Standard

See extended version: ▶2.3

Buildings which do not comply with one or more of the Passive House or EnerPHit criteria may still satisfy the PHI Low Energy Building Standard.

Table 5 PHI Low Energy Building criteria

			Criteria[1]	Alternative Criteria[2]
Heating				
Heating demand	[kWh/(m²a)]	≤	30	
Cooling				
Cooling + dehumidification demand	[kWh/(m²a)]	≤	Passive House requirement[3] + 15	
Airtightness				
Pressurization test result n_{50}	[1/h]	≤	1.0	
Renewable Primary Energy (PER)[4]				
PER demand[5]	[kWh/(m²a)]	≤	75	Exceeding the criteria up to +15 kWh/(m²a) is permitted...
Renewable energy generation[6] (with reference to projected building footprint)	[kWh/(m²a)]	≥	-	...with compensation of the above deviation by additional generation[7]

[1] **Criteria:** See footnote 1 of the Passive House criteria on Table 1.
[2] **Alternative criteria:** See footnote 2 of the Passive House criteria on Table 1.
[3] **Cooling and dehumidification demand:** See footnote 1 of the EnerPHit energy demand criteria on **Table 3**.
[4] **Renewable Primary Energy:** See footnote 5 of the Passive House criteria on Table 1.
[5] **PER demand:** See footnote 6 of the Passive House criteria on Table 1.
[6] **Renewable energy generation:** See footnote 7 of the Passive House criteria on Table 1.
[7] **Alternative PER criteria:** See footnote 8 of the Passive House criteria on Table 1.

Figure 0.2. Alternative PH standard source:(PHI 2023)

Appendix B: Roof Optimisation and Comparison for the 5 Saudi Climate Zone

No	Parameter/City Name	Madinah	Riyadh	Dammam	Tabuk	Abha	Insulation Thickness	Main highlight	Note
	SBC Climate Zone		Zone 1		Zone 2	Zone 3	All Zones		What impact for each zone?
1	SBC Case Model	31,153.00	26,670.74	26,327.40	19,450	16,288.33		SBC zoning-based U-Value	SBC reference case
	Research Climate Zone	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5			
2	Passivhaus (U-Value 0.15)	26,213.05	23,507.43	22,883.30	15,342.50	7,684.03	21.41 cm	Passivhaus required	The baseline consumption
3	Scenario 1 (U-Value 0.10)	25,254.06	22,853.58	22,267.79	14,961.61	7,682.03	33.08 cm	Largest thickness	
4	Change (vs. Baseline)	-3.66%	-2.78%	-2.69%	-2.48%	-0.03%	+54.5%	All reduces energy consumption	High cost for small savings
5	Scenario 2 (U-Value 0.20)	27,068.27	24,446.91	23,392.62	15,674.62	7,685.28	15.58 cm	Middle thickness	
6	Change (vs. Baseline)	+3.26%	+4.00%	+2.23%	+2.16%	+0.02%	-27.2%	All increase energy consumption	Great cost-benefit (3&4)
7	Scenario 3 (U-Value 0.30)	28,814.54	25,974.05	24,384.59	16,340.30	7,702.62	9.74 cm	Smallest thickness	
8	Change (vs. Baseline)	+9.92%	+10.49%	+6.56%	+6.50%	+0.24%	-54.5%	All increases energy consumption	Excellent cost-benefit (Zone 5)
9	Optimal Choice (Cost-Benefit)	U-Value 0.15	U-Value 0.15	U-Value 0.20	U-Value 0.20	U-Value 0.30	Climate-Specific	Best balance of cost & performance	
10	Key Finding	Baseline is balanced	Baseline is balanced	Thinner insulation is better	Thinner insulation is better	Minimal insulation is best		Passivhaus is not "one size fits all"	

Appendix C: The Saudi Building Code

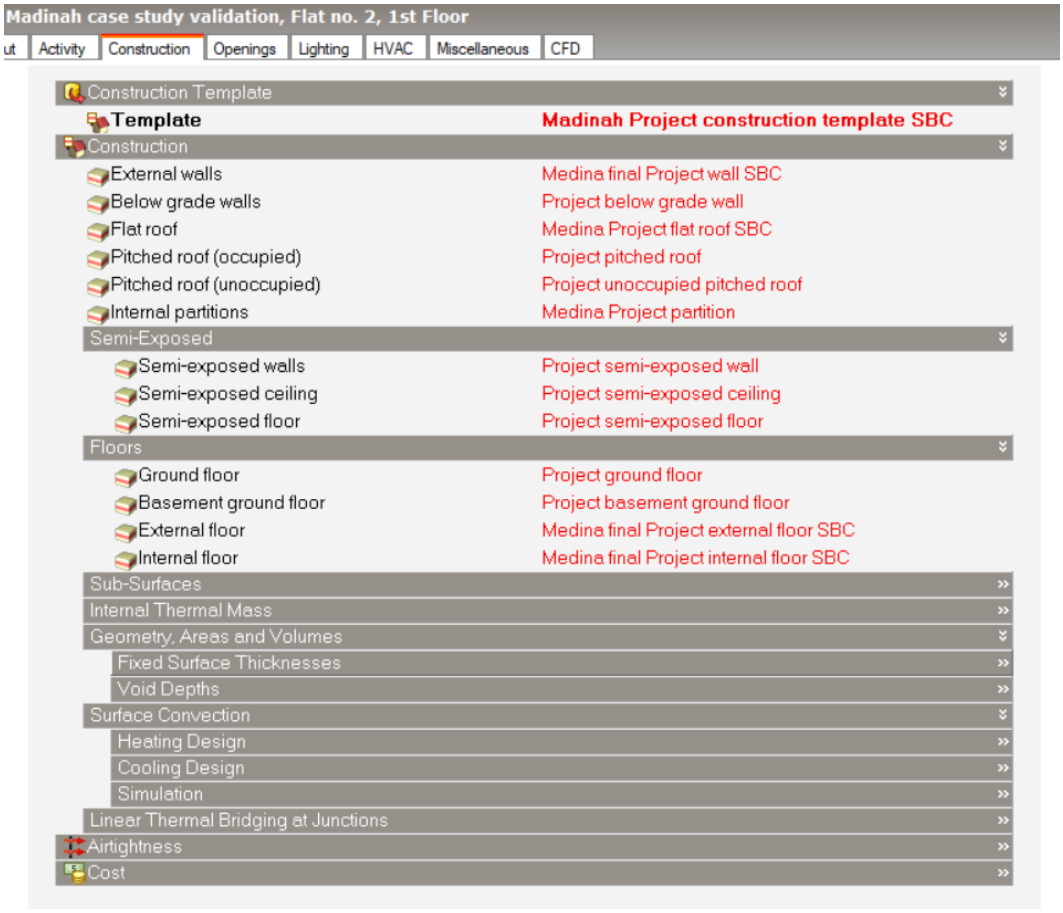


Figure 0.3. Creating SBC Requirements Template

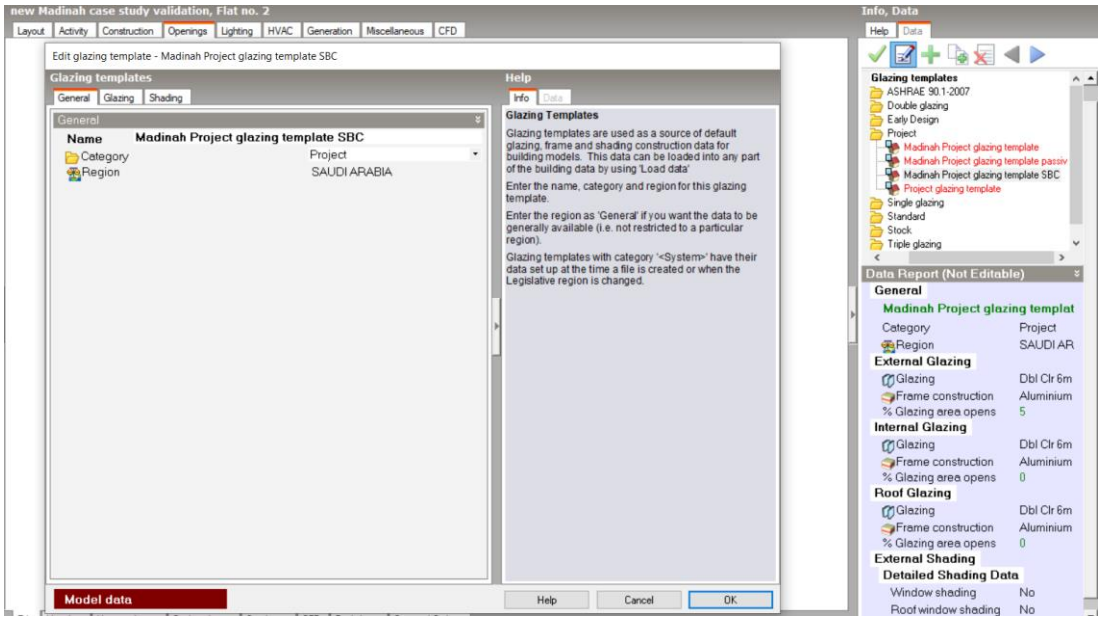
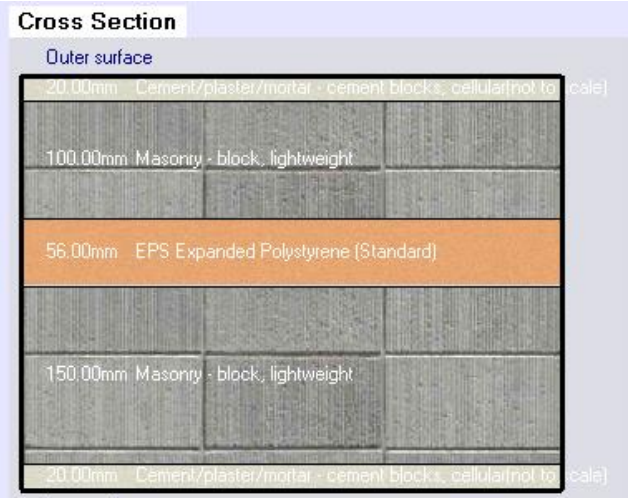


Figure 0.4. Double-glazed window utilised in Madinah SBC



Inner surface	
Convective heat transfer coefficient (W/m2-K)	2.152
Radiative heat transfer coefficient (W/m2-K)	5.540
Surface resistance (m2-K/W)	0.130
Outer surface	
Convective heat transfer coefficient (W/m2-K)	19.870
Radiative heat transfer coefficient (W/m2-K)	5.130
Surface resistance (m2-K/W)	0.040
No Bridging	
U-Value surface to surface (W/m2-K)	0.361
R-Value (m2-K/W)	2.941
U-Value (W/m2-K)	0.340
With Bridging (BS EN ISO 6946)	
Thickness (m)	0.3460
Upper resistance limit (m2-K/W)	2.941
Lower resistance limit (m2-K/W)	2.941
U-Value surface to surface (W/m2-K)	0.361
R-Value (m2-K/W)	2.941
U-Value (W/m2-K)	**0.340**

Figure 0.5. Zone 1 Wall requirements as SBC

Table 0.1. Climatic Data of Selected Saudi Cities source: SBC 602

					10 year (SI)			
			Zone	Elevation	DB 1%	DB max	CDD18.3	CDD10
	Latitude	Longitude		m	C	C		
ABHA	18.23N	42.65E	3	2093	30.3	34	768	3289
AL-AHSA	25.30N	49.48E	1	178	46	49.8	3573	6389
AL-BAHA	20.30N	41.65E	2	1652	35.2	39	1925	4781
AL-JOUF	29.78N	40.10E	2	689	41.8	46.7	2279	4612
AL-MADINAH	24.55N	39.70E	1	636	44.2	47.7	3757	6715
AL-QAISUMAH	28.32N	46.13E	1	358	45.2	50.4	3156	5706
AL-TAIF	21.48N	40.55E	2	1453	36.1	41	1972	4804
AL-WEJH	26.20N	36.48E	2	24	34.2	44.7	2483	5493
ARAR	30.90N	41.13E	2	549	42.3	47.3	2315	4571
BISHA	19.98N	42.63E	1	1162	39.8	42.8	2701	5640
DHAHRAN	26.27N	50.17E	1	17	44	49.3	3398	6258

Appendix D:

Table 0.2. Weather stations in Saudi Arabia source: (Said, Habib et al. 2003)

City	Elevation (m)	Latitude (north)		Longitude (east)		Climatic zones
		deg.	min	deg.	min	
Taif	1454	21	29	40	33	1
Bisha	1163	19	58	42	37	1
Khamis Mushayt	2057	18	18	42	48	1
Najran	1210	17	37	44	26	1
Jeddah	18	21	40	39	09	2
Gizan	3	16	51	42	35	2
Al-Wedjh	21	26	12	36	28	2
Yanbu	6	24	09	38	04	2
Dhahran	17	26	16	50	10	3
Turaif	818	31	41	38	40	4
Arar	552	30	54	41	08	4
Al-Jouf	684	29	47	40	06	4
Rafha	447	29	38	43	29	4
Qaisumah	360	28	20	46	07	4
Tabuk	776	28	22	36	38	4
Hail	1013	27	26	41	41	4
Madina	636	24	33	39	42	4
As-Sulayel	614	20	28	45	37	5
Gassim	650	26	18	43	46	5
Riyadh	612	24	56	46	43	5

Appendix E:

Table 0.3. ASHRAE climate zoning for Saudi Arabia (ASHRAE, 2021)

Country Location	WMO #	Latitude	Longitude	Climate Zone
Saudi Arabia (SAU)				
ABHA	411120	18.24	42.657	2B
AL AQIQ	410550	20.296	41.634	2B
AL JOUF	403610	29.785	40.1	2B
AL WAJH	404000	26.199	36.476	1B
AL-AHSA	404200	25.285	49.485	0B
ARAR	403570	30.907	41.138	2B
BISHA	410840	19.984	42.621	1B
DAMMAM KING FAHD INTL	404150	26.433	49.8	0B
DHAHARAN KING ABDULAZIZ AB	404160	26.265	50.152	0B
GASSIM	404050	26.3	43.767	1B
GURAYAT	403600	31.412	37.279	2B
HAIL	403940	27.438	41.686	2B
JEDDAH KING ABDULAZIZ INTL	410240	21.68	39.157	0B
JIZAN	411400	16.896	42.584	0B
KHAMIS MUSHAIT	411140	18.297	42.804	2B
MAKKAH	410300	21.437	39.77	0B
MEDINA PRINCE ABDULAZIZ INTL	404300	24.553	39.705	0B
NAJRAN	411280	17.611	44.419	1B
QAISUMAH	403730	28.335	46.125	1B
RAFHA	403620	29.626	43.491	1B
RIYADH KING KHALED INTL	404370	24.958	46.699	1B
RIYADH KING SALMAN AB	404380	24.722	46.725	0B
SHARORAH	411360	17.467	47.121	0B
TABUK	403750	28.365	36.619	2B
TAIF	410360	21.483	40.544	2B
TURAIF	403560	31.693	38.731	2B
WADI AL DAWASIR	410610	20.504	45.2	0B
YANBU PRINCE ABDULAZIZ	404390	24.144	38.063	0B

Appendix F:

Table 0.4. Simulated Energy Performance: Baseline vs. SBC Models in Madinah

Category (kWh)	SBC Modelling	Base Case Study	Difference	%
Total Site Energy	31153	37015	5862.13	-15.84%
Total Cooling	24513	30214	5700.75	-18.87%
Interior Equipment	5556	5672	115.86	-2.04%
Interior Lighting	991	1031	40.1	-3.89%
District Heating [water]	93	98	5.41	-5.52%

Table 0.5. Simulated Energy Performance: Baseline vs. SBC Models in Riyadh

Category (kWh)	SBC Model	Base Model	Difference	%
Total Site Energy	26,671	31,795	5124.26	-16.12%
Total Cooling	20,185	24,994	4808.64	-19.24%
Interior Equipment	5,402	5,672	270.11	-4.76%
Interior Lighting	991	1,031	40.1	-3.89%
District Heating [water]	93	98	5.41	-5.52%

Table 0.6. Simulated Energy Performance: Baseline vs. SBC Models in Dammam

Category (kWh)	SBC Model	Base Model	Difference	%
Total Site Energy	26,327	31,920	5592.6	-17.52%
Total Cooling	19,842	25,120	5277.97	-21.01%
Interior Equipment	5,402	5,672	270.11	-4.76%
Interior Lighting	991	1,031	40.1	-3.89%
District Heating [water]	93	98	5.41	-5.52%

Table 0.7. Simulated Energy Performance: Baseline vs. SBC Models in Tabuk

Category (kWh)	SBC Model	Base Model	Difference	%
Total Site Energy	19,450	23,843	4392.68	-18.42%
Total Cooling	13,007	17,042	4034.49	-23.67%
Interior Equipment	5,359	5,672	313.19	-5.52%
Interior Lighting	991	1,031	40.1	-3.89%
District Heating [water]	93	98	5.41	-5.52%

Table 0.8. Simulated Energy Performance: Baseline vs. SBC Models in Abha

Category (kWh)	SBC Model	Base Model	Difference	%
Total Site Energy	16288.33	25754.19	9465.86	-36.75%
Total Cooling	9648.71	18953.31	9304.6	-49.09%
Interior Equipment	5556.14	5672.39	116.25	-2.05%
Interior Lighting	991	1,031	40.1	-3.89%
District Heating [water]	93	98	5.41	-5.52%

Appendix G: First-Year PGR Pitch Perfect PhD

Dr Siddig Omer nominated me to compete in the BEE Engineering Showcase Event 2022, which took place in March 2022. Fig 0.6 depicts the poster, which has three main parts: stating the problem in the Saudi buildings sector, proposing a solution, and concluding with the goals. A one-minute recording was submitted with the one-slide presentation demonstrating the primary information.

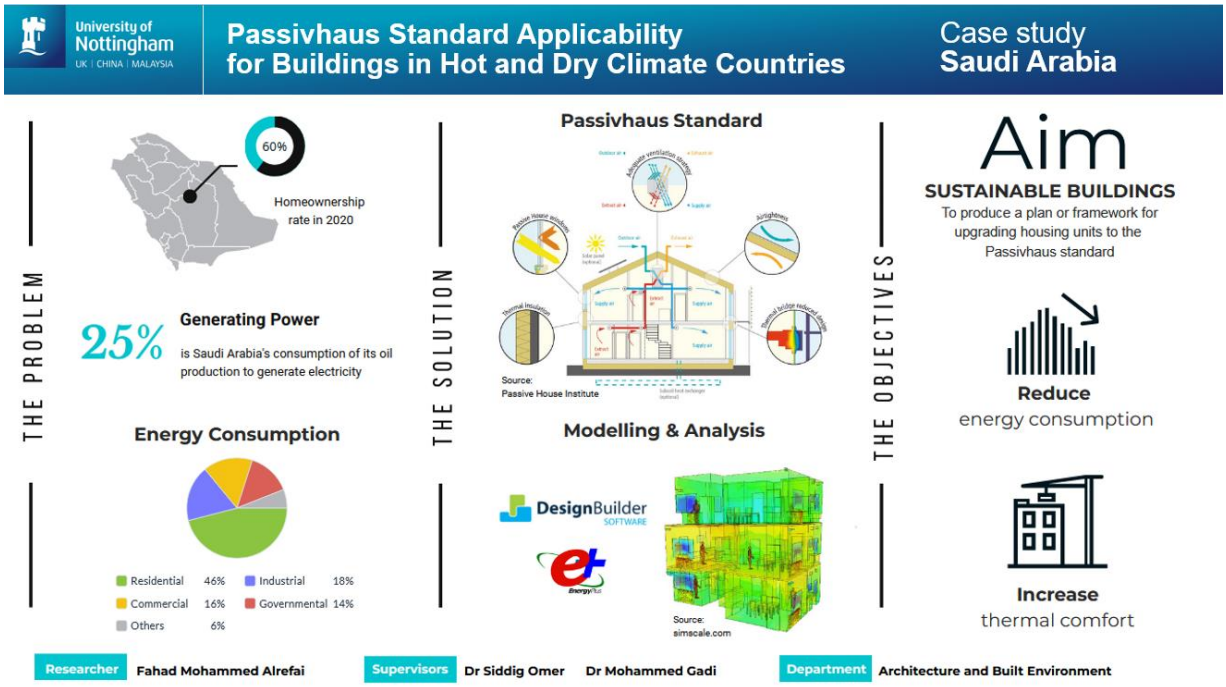


Fig 0.6. My participation in the Engineering Showcase event 2022

Appendix H: Research Integrity Training Certificate

University of Nottingham
UK | CHINA | MALAYSIA

Certificate of Attendance

Mr Fahad Alrefai

has completed the following training course(s)

Course Name	Course Date(s)	Training Units obtained	Sessions in course	Sessions Attended
Research integrity: concise (standalone online learning course)	01-10-2021	0.00	0	1

L Donaldson

Professor Lucy Donaldson
Associate Pro-Vice Chancellor for the Researcher Academy and Research Career Development

R Cowley

Mr Richard Cowley
Co-Director of Professional Development

Appendix I:

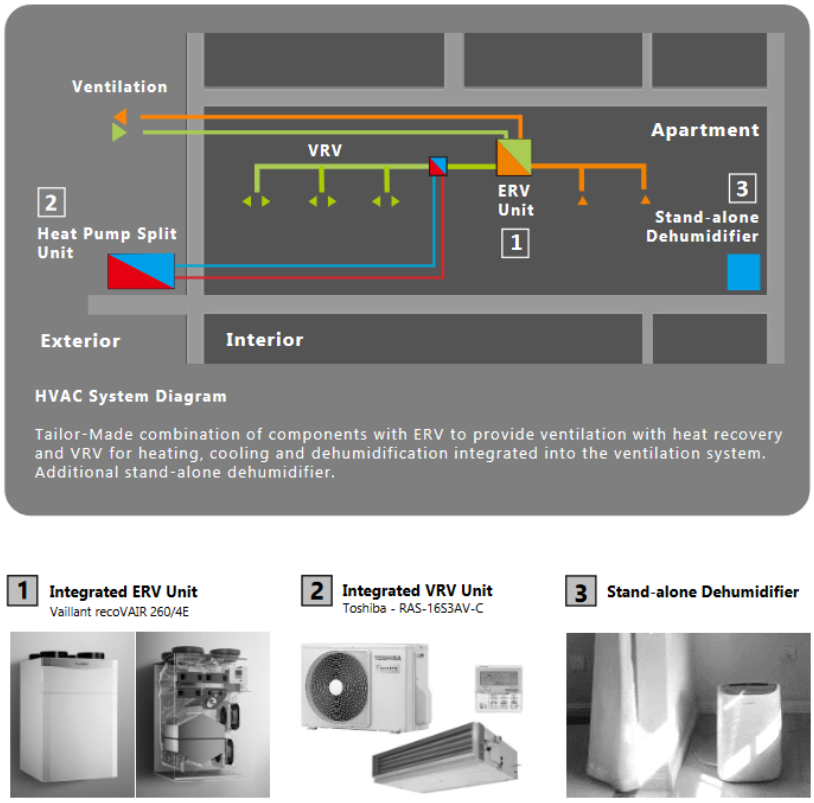


Figure 0.7. HVAC system designed (Passive House Institute 2019)

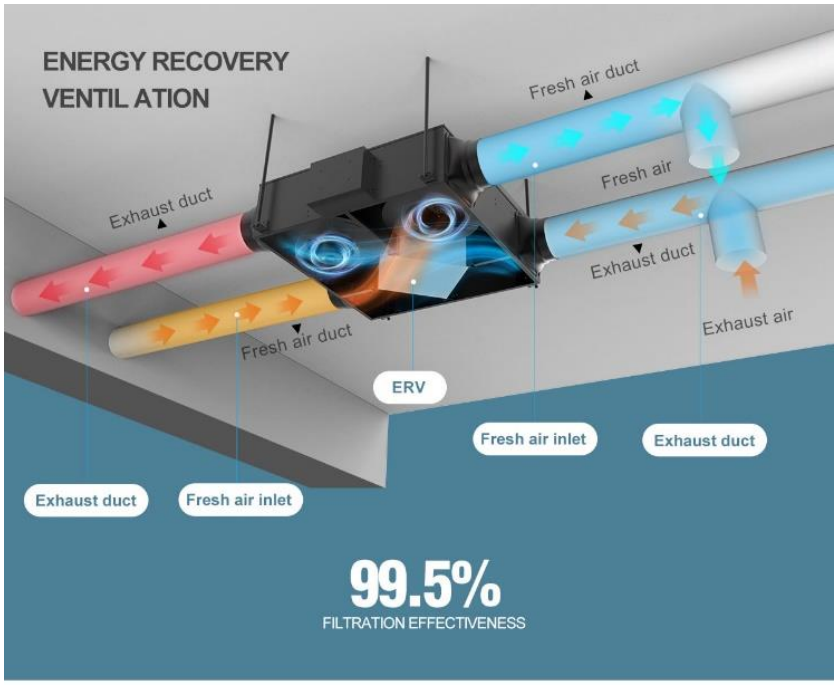


Figure 0.8. Recommended ERV System

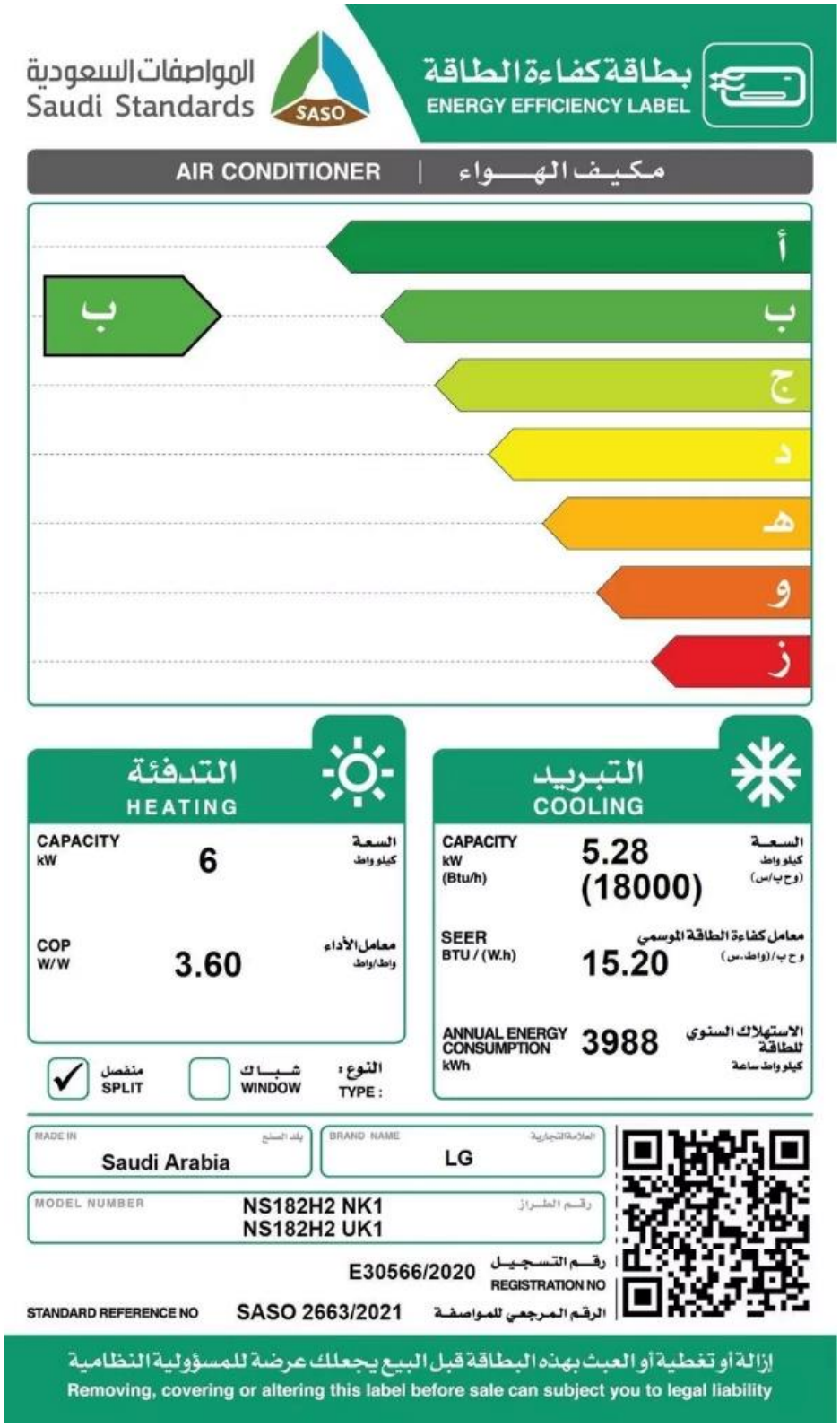


Figure 0.9 SASO Energy Efficiency Label for Selected LG Split AC Unit

Appendix J:

Passive House Verification



Building:	pilot project "Passive House in Dubai"		
Street:	Al Khawaneej Street		
Postcode/City:		Al Khawaneej	
Province/Country:	Dubai	AE-Vereinigte Arabische Emirate	
Building type:	office building		
Climate data set:	AE0001a-Dubai		
Climate zone:	7: Very hot	Altitude of location:	6 m
Home owner / Client:	MBRSC - Mohammed Bin Rashid Space Centre		
Street:	Al Khawaneej Street		
Postcode/City:		Al Khawaneej	
Province/Country:	Dubai	AE-Vereinigte Arabische Emirate	

Architecture:	Casetta&Partners		
Street:	via Verdi, 67		
Postcode/City:	31046	Oderzo	
Province/Country:	Treviso	IT-Italien	
Energy consultancy:	University of Bergamo - Dept. of Engineering and Applied Scier		
Street:	Viale Marconi, 5		
Postcode/City:	24044	Dalmine	
Province/Country:	Bergamo	IT-Italien	
Mechanical system:	Energy Plus Project		
Street:	piazzetta San Marco, 7/8		
Postcode/City:	31053	Pieve di Soligo	
Province/Country:	Treviso	IT-Italien	
Certification:			
Street:			
Postcode/City:			
Province/Country:			

Year of construction:	2016	Interior temperature winter [°C]:	19,4	Interior temp. summer [°C]:	25,0
No. of dwelling units:	1	Internal heat gains (IHG) heating case [W/m²]:	2,8	IHG cooling case [W/m²]:	2,8
No. of occupants:	16,0	Specific capacity [Wh/K per m² TFA]:	84	Mechanical cooling:	x

Specific building characteristics with reference to the treated floor area

					Criteria	Alternative criteria	Fulfilled?[2]
	Treated floor area	m²	410,8				
Space heating	Heating demand	kWh/(m²a)	0	≤	15	-	yes
	Heating load	W/m²	-	≤	-	-	
Space cooling	Cooling & dehum. demand	kWh/(m²a)	50	≤	19	57	yes
	Cooling load	W/m²	9,7	≤	-	10,7	
	Frequency of overheating (> 25 °C)	%	-	≤	-		-
	Frequency excessively high humidity (> 12 g/kg)	%	0	≤	10		yes
Airtightness	Pressurization test result n_{50}	1/h	0,48	≤	0,6		yes
Non-renewable Primary Energy (PE)	PE demand	kWh/(m²a)	143	≤	-		-
Primary Energy Renewable (PER)	PER demand	kWh/(m²a)	73	≤	60	73	yes
	Generation of renewable energy (in relation to projected building	kWh/(m²a)	185	≥	-	19	

[2] Empty field: Data missing; '-': No requirement

excerpt from Verification sheet in PHPP

Figure 0.10 PHPP calculations for Dubai Project (MBRSC)

Appendix K:

Summary of key literature on the Passivhaus standard and building energy performance

Reference Title	Authors Name/Year
Towards Sustainable Residential Buildings in the Kingdom of Saudi Arabia	(Taleb 2012)
Challenges Facing the Application of Zero-Energy Homes in Saudi Arabia: Construction Industry and User Perspective	(Alrashed and Asif 2012)
Challenges Facing the Application of Sustainability to Housing in Saudi Arabia	(Al Surf, 2014)
25 Years of Passive House - Interview with Dr. Wolfgang Feist	(Feist 2015)
Passivhaus in the UK: the Challenges of an Emerging Market. A Case Study of Innovation Using Mixed Methods Research	(Lynch, 2014)
The First Passivhaus in Qatar: Initial Monitoring and Modelling Energy Performance	(Khalfan, Sharples et al. 2015)
The Passivhaus Standard in the Mediterranean Climate: Evaluation, Comparison and Profitability	(Saldaña-Márquez, Gómez-Soberón et al. 2015)
Optimal Design of Residential Building Envelope Systems in the Kingdom of Saudi Arabia	(Alaidroos and Krarti 2015)
High Performance Homes in Saudi Arabia Revised Passivhaus Principles for Hot and Arid Climates	(Alshenaif 2015)
The Present and Future Energy Performance of the First Passivhaus Project in the Gulf Region	(Khalfan and Sharples 2016)
The Impact of Construction and Building Materials on Energy Consumption on Saudi Residential Buildings	(Lasker 2016)
Design Principles for Thermally Comfortable and Low Energy Homes in the Extreme Hot-Humid Climatic Gulf Region, with reference to Dammam, Saudi Arabia	(Alshaikh 2016)
Evaluation of Net-Zero Energy Residential Buildings in the MENA Region	(Krarti and Ihm 2016)
An Assessment of the Passivhaus Standard for a Hot and Arid Climate: a Case Study in Qatar	(Khalfan, 2017)

Energy Efficient Strategies for the Building Envelope of Residential Tall Buildings in Saudi Arabia	(Ghabra 2018)
Smart Solutions to Manage Peak Electricity Demand in Saudi Arabia	(Alshahrani 2018)
Lessons Learned from the First Passivhaus Building in Qatar	(Khalfan 2019)
Application of Building Performance Simulation to Design Energy-Efficient Homes: Case Study from Saudi Arabia	(Ahmed, Asif et al. 2019)
Two Residential Passive House Towers in Tianjin Eco-City (Bldg. #4)	(Passive House Institute 2019)
The Passivhaus Standard in the Spanish Mediterranean: Evaluation of a House's Thermal Behaviour of Enclosures and Airtightness	(Echarri-Iribarren, Sotos-Solano et al. 2019)
Impact of Glazing to Wall Ratio in Various Climatic Regions: A Case Study	(Alwetaishi 2019)
Residential Building Stock Model for Evaluating Energy Retrofit Programs in Saudi Arabia	(Krarti, Aldubyan et al. 2020)
An Assessment of the Saudi Residential Buildings Envelope Code Under the Current and Future Climate Change Scenarios: the Case for Jeddah in the Hot and Humid Climate Region	(Abuhussain 2020)
An Optimum Thermal Insulation Type and Thickness for Residential Buildings in Three Different Climatic Regions of Saudi Arabia	(Al-Tamimi 2021)
Towards Sustainable Residential Buildings in Saudi Arabia According to the Conceptual Framework of "Mostadam" Rating System and Vision 2030	(Balabel and Alwetaishi 2021)
Evaluating Passivhaus EnerPHit Retrofit Strategies for Low-Rise Suburban Dwellings in China's Hot Summer-Cold Winter Climate Region	(Liu 2021)
Performance Gap in a Multi-Storey Student Accommodation Complex Built to Passivhaus Standard	(Kang, Chang et al. 2021)
Optimization of the Passive House Concept for Residential Buildings in the South-Brazilian Region	(Vettorazzi, 2021)

An Approach to Enhancing Energy Performance in Residential Buildings in Hot Climate Regions (The Case of Saudi Arabia)	(Alyami 2022)
Review of Adoption Status of Sustainable Energy Technologies in the US Residential Building Sector	(Schwartz and Krarti 2022)