UNIVERSITY OF CAPE TOWN
IYUNIVESITHI YASEKAPA • UNIVERSITEIT VAN KAAPSTAD

AN INVESTIGATION OF THE ENERGY AND ENVIRONMENTAL SUSTAINABILITY IMPACT OF AFFORDABLE NET-ZERO ENERGY HOUSE IN SOUTH AFRICA

Prepared by:

Dylan Hübner

Supervisor:

Professor Kathleen Michell

Doctor Alireza Moghayedi

27 January 2025

Department of Construction Economics and Management, Faculty of Engineering and the Built Environment, University of Cape Town

PLAGIARISM DECLARATION

1. I know that plagiarism is a serious form of academic dishonesty.

2. I have read the document about avoiding plagiarism, I am familiar with its contents and have avoided all forms of plagiarism mentioned there.

3. Where I have used the words of others, I have indicated this using quotation marks.

4. I have referenced all quotations and other ideas borrowed from others.

5. I have not and shall not allow others to plagiarise my work.

Signature: __ Signed by candidate

ABSTRACT

This dissertation is submitted in fulfilment of the requirements for the degree of Master of Philosophy (MPhil) in Construction Economics and Management at the University of Cape Town.

This study aims to explore the energy and environmental sustainability implications linked to affordable net-zero energy housing in South Africa. Affordable housing is intended for individuals who cannot afford market related prices or do not meet the criteria for social housing. Accordingly, this dissertation defines affordability as households spending no more than 30% of their income on gross housing expenses. It seeks to provide insights into the challenges, opportunities, and implications of integrating net-zero energy housing into the affordable housing sector. Given South Africa’s shortage of affordable housing, unstable electricity supply, and economic challenges, there is significant opportunity to explore alternative building strategies to address these issues.

The research employed an exploratory mixed-method approach rooted in the philosophical foundations of realism. Qualitative data was procured through 4 in-depth semi-structured interviews conducted with 3 sustainability professionals and an affordable housing specialist. Quantitative modelling utilised One Click LCA and the Edge App to estimate the life cycle carbon emissions of an affordable net-zero energy house.

The findings indicate that affordable net-zero energy housing can substantially reduce both operational and embodied carbon emissions. By integrating conventional building practices with innovative methods, the life cycle emissions of a house are significantly reduced, surpassing sustainable building regulation requirements. The quantitative analysis of three affordable net-zero energy housing scenarios, incorporating both conventional and innovative building techniques and practices across different levels to mimic South Africa's construction landscape, demonstrates a potential reduction in life cycle carbon emissions ranging from 12% to 94%. Furthermore, South Africa's landscape may not be conducive to net-zero embodied energy houses, suggesting that developers and households should prioritise reducing operational carbon emissions. These findings contribute to knowledge within the professional, affordable, and sustainable housing spaces, thereby facilitating informed decision-making towards a more sustainable and affordable South African residential sector.

ACKNOWLEDGEMENTS

The author would like to thank all the individuals who supported and played a critical role in making this research possible:

First and foremost, my deepest thanks go to my supervisors, Dr. Alireza Moghayedi and Professor Kathy Michell. Your unwavering support, insightful mentorship, and scholarly guidance have been instrumental throughout my journey. Your commitment to my progress kept me focused and made the writing process smooth and productive. I am truly grateful for your encouragement and invaluable contributions.

I would also like to extend my sincere appreciation to all the interviewees who generously shared their time, knowledge, and professional expertise. Your insights were crucial to shaping and refining this thesis.

Finally, I am grateful to my family and friends for their constant moral support and encouragement.

Thank you all for making this possible.

TABLE OF CONTENTS

PLAGIARISM DECLARATION i

ABSTRACT ii

ACKNOWLEDGEMENTS iii

TABLE OF CONTENTS iv

LIST OF FIGURES viii

LIST OF TABLES ix

ABBREVIATIONS x

1 INTRODUCTION 1

1.1 Introduction 1

1.2 Rationale for the Study 2

1.3 Problem Statement 7

1.4 Research Question 7

1.5 Research Aim 8

1.6 Research Objectives 8

1.7 Overview of Research Methodology 8

1.8 Scope And Limitations 9

1.9 Dissertation Structure 9

2 LITERATURE REVIEW 10

2.1 Introduction 10

2.2 Overview of Affordable Housing 10

2.2.1 Affordable Housing Within an International Context 10

2.2.2 What is Affordable Housing? 12

2.2.3 Extent of Affordable Housing in South Africa 16

2.2.4 Challenges Faced by Affordable Housing in South Africa 18

2.3 Sustainability in the Built Environment 22

2.3.1 Economic Pillar of Sustainability 23

2.3.2 Social Pillar of Sustainability 24

2.3.3 Environmental Pillar of Sustainability 24
2.4 Understanding Sustainable Development 25
2.5 Sustainability Within the Affordable Housing Context 26
2.6 Energy Consumption According to South Africa's Building Regulations 29
2.6.1 Building Envelope 31
2.6.2 Building Services 34
2.7 Affordable Net-zero Energy House 34
2.7.1 ANZEB Design Techniques, Features, and Technologies 39
2.8 Carbon Emission Life Cycle Analysis 50
2.9 Adopted Theoretical Framework 52
2.9.1 Theory of Change 53
2.9.2 Conceptual Framework 54
2.10 Research Gap 57
2.11 Summary of the Chapter 58
3 RESEARCH METHODOLOGY 60
3.1 Introduction 60
3.2 Research Philosophy 60
3.3 Research Paradigm 61
3.3.1 Qualitative Approach 62
3.3.2 Quantitative Approach 63
3.3.3 Mixed Method Approach 63
3.4 Research Approach 64
3.5 Adopted Strategy and Research Approach 66
3.6 Method of Data Collection 67
3.6.1 Qualitative Data Collection 67
3.6.2 Quantitative Data Collection 70
3.7 Method of Data Analysis 72
3.7.1 Qualitative Data Analysis 72

3.7.2 Quantitative Data Analysis 73
3.8 Validity & Reliability of the Data 75
3.9 Ethical Considerations 77
3.10 Summary of the Chapter 78
4 DATA ANALYSIS AND RESULTS 79
4.1 Introduction 79
4.2 Participant Backgrounds 79
4.3 Qualitative Analysis 80
4.3.1 Professional Viewpoint of Affordable Housing In South Africa 80
4.3.2 Affordable Net-Zero Energy Housing 84
4.3.3 Affordable Net-zero Energy Housing Dimensions 88
4.3.4 Attributes and Characteristics of an ANZEH 100
4.4 Quantitative Analysis 103
4.4.1 Affordable Net-zero Energy House Case Structure 103
4.4.2 Cross Scenario Analysis Overview 114
4.4.3 Embodied V Operational Carbon Emission Analysis 120
4.4.4 Whole Life Cycle Cost Analysis 122
4.5 Discussion of the Findings 123
4.6 Summary of the Chapter 130
5 CONCLUSION 132
5.1 Introduction 132
5.2 Revisiting Research Questions, Aim, and Objectives 132
5.3 Significance of the Research 134
5.4 Conclusion 135
5.5 Contribution to Knowledge 137
5.6 Recommendations 138
5.7 Recommended Further Research 139
Appendices 161

Appendix A: Questionnaire 161

Appendix B: NVivo Tree Node Structure.. 163

Appendix C: NVivo Tree Node Map 165

Appendix D: Ethics Clearance 166

Appendix E: Consent Form 167

LIST OF FIGURES

Figure 2.1: Generic apartheid city plan (Davies, 1981) 17
Figure 2.2: Breakdown of total property operating costs by percentage (SAPOA, 2022) 21
Figure 2.3: SANS 10400-XA building type classifications (SANS 10400-XA, 2011) 30
Figure 2.4: SANS 10400-AX energy zone map of South Africa (TIPSASA, 2022)... 30
Figure 2.5: Life cycle carbon emission breakdown (Ibn-Mohammed et al., 2013).... 38
Figure 2.6: ANZEH dimensions 39
Figure 2.7: Whole carbon life cycle assessment framework (RICS, 2023)............... 51
Figure 2.8: ANZEH sustainability framework 54
Figure 2.9: ANZEHs design framework flow.. 56
Figure 3.1: Research development timeline 65
Figure 3.2: Exploratory mixed method approach (Subedi, 2016) 66
Figure 4.1: Affordable 3-bedroom house floor plan 103
Figure 4.2: 3D model of the 3-bedroom affordable house 104
Figure 4.3: Upfront carbon emission savings against the base case 116
Figure 4.4: In-use carbon emissions savings against the base case 118
Figure 4.5: End of life carbon emissions savings against the base case................ 118
Figure 4.6: Information beyond construction works life cycle carbon emissions savings against the base case 119
Figure 4.7: Whole life cycle carbon emission module breakdown 120

LIST OF TABLES

Table 2.1: Types of affordable housing measures 14
Table 2.2: Heating and Cooling Energy Required 31
Table 2.3: Maximum energy consumption of residential units per climate region 31
Table 2.4: Minimum prudence factor of a shading device 32
Table 2.5: Floor classification and R-value requirements of a floor 32
Table 2.6: Masonry wall R-value requirements 33
Table 2.7: Cavity wall and insulation greater than 50mm R-value requirements...... 33
Table 2.8: Roof R-value requirements... 33
Table 2.9: Hot water piping insulation R-value requirements 34
Table 2.10: Summary of ANZEH critical success factors 48
Table 4.1: Participant Backgrounds 80
Table 4.2: ANZEH attributes and characteristics summarised 102
Table 4.3: Room dimensions.. 104
Table 4.4: OneClick LCA material input parameters 107
Table 4.5: Edge App material and technological parameters................................ 108
Table 4.6: Whole life cycle carbon emissions assessment for the 3 ANZEH scenarios 115
Table 4.7: Embodied carbon emission savings 121
Table 4.8: Operational carbon emission savings.. 121
Table 4.9: Embodied v operational carbon emissions 122
Table 4.10: Whole life cycle cost of the modelled scenarios 122

ABBREVIATIONS

Abbreviation	Definition
ASHP	Air Source Heat Pump
ANZEH	Affordable Net-Zero Energy House
BREEAM	Building Research Establishment Environmental Assessment Method
CAH	Conventional Affordable Housing
CAHF	Centre for Affordable Housing
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
EPC	Energy Performance Certificate
GBCSA	Green Building Council of South Africa
GHG	Greenhouse Gas
IES	Integrated Environmental Solutions
IFC	International Finance Corporation
LCA	Life Cycle Assessment
LED	Light Emitting Diode
LEED	Leadership in Energy and Environmental Design
LCCE	Life Cycle Carbon Emission
NBR	National Building Regulation
NZEB	Net-Zero Energy Building
PV	Photovoltaic
RDP	Reconstruction and Development Programme
SANS	South African National Standards
SAPOA	South African Property Owners Association

1 INTRODUCTION

1.1 Introduction

Developing nations are faced with settlement development challenges within the context of rapid urbanisation, housing shortages, inadequate infrastructure, higher urban costs, and environmental degradation (Zhang, 2016). Landman and du Plessis (2002) iterated in 2002, South Africa's urban settlements were faced with these challenges which created an unsustainable urban development trend. Nearly 20 years later, the 2021 General Household Survey conducted by Statistics South Africa (2022b), found that 11.7% of South Africans live in informal housing. This observation indicates that there is a need for affordable housing which will promote sustainable development, and help South Africa improve access to adequate housing and reduce the number of citizens living in informal settlements.

Furthermore, the demand for domestic energy has risen as the increase in grid supplied electricity connections increased from 76.7% in 2002 to 89.3% in 2021 (Statistics South Africa, 2022b). The resulting increase in pressure on South Africa's ailing electricity infrastructure and power generation facilities which has resulted in loadshedding and economic turmoil (Lenoke, 2017). This has left the country in an electricity supply deficit with a continually growing electricity demand resulting in a 'Declaration of a National State of Disaster: Impact of Severe Electricity Supply Constraints' being issued on the 09 February 2023 (South African Government, 2023a).

These energy challenges are not limited to South Africa and globally, the need for alternative green energy solutions has become increasingly urgent. Many countries are promoting energy efficient developments and encouraging with greater on-site renewable energy generation. This has sparked particular interest in net-zero energy buildings (NZEB). NZEBs are designed to consume only as much energy annually as it can generate through on-site or off-site renewable sources (Teja, 2018). By integrating solar panels, energy-efficient and smart technologies, NZEBs will lower operational costs and energy demands. This in turn, will ease the burden on overstretched power infrastructure by decreasing the reliance on the national energy grid.

Therefore, this dissertation seeks to merge the affordable and NZEB concepts to understand the energy and environmental sustainability impact of affordable net-zero energy houses (ANZEH) in South Africa. While this study references both energy and carbon emissions, the primary focus is on energy. The term "energy" is discussed throughout the research, and it serves as a proxy for establishing carbon emissions. For clarity, the term energy encompasses all forms of energy consumption whether electricity or fuels used in the extraction and processing of raw materials, construction, operational use, maintenance, and demolition of a building. The goal of NZEB is to produce as much renewable energy as it consumes annually to achieve an energy balance. This typically involves energy efficient systems, solar systems and battery storage. In contrast, carbon emissions refer to the associated greenhouse gas (GHG) emissions resulting from the energy consumption process.

1.2 Rationale for the Study

The need to accelerate the adoption of a more sustainable built environment has become evident in the 20th century. Rising global temperatures and sea levels, rapidly changing climates and more severe weather have highlighted the impact of global warming. Nations across the globe have begun to strive for net-zero emissions by 2050 to restrict the global temperature rise to 1.5 degrees Celsius (International Energy Agency, 2021). At the same time, the inequality gap is also increasing as the world becomes more technologically advanced (Branson *et al.*, 2012). This inequality gap is preventing the adoption and integration of sustainable developments into low-income households (International Monetary Fund, 2024).

The built environment produces significant amounts of GHGs throughout its construction and operational life cycles. According to the International Energy Agency (2020), buildings contribute directly to 9% of carbon dioxide (CO_2) emissions. Patel and Chugan (2013) further emphasise that the construction industry is a major contributor to these emissions, with the built environment consuming roughly a third of the world's energy. The embodied energy required to construct a building encompasses mined and grown materials, manufacturing, transportation, construction, and demolition which significantly contributes towards environmental degradation and the production of GHG emissions (Levermore, 2008; Roh *et al.*, 2014; Balouktsi *et al.*, 2020). The operational phase of a building consumes significant amounts of electricity, which is predominantly fossil fuel produced. Consequently, carbon emissions have been identified as the main contributor towards global warming due to energy being produced through the combustion of fossil fuels (Cropper *et al.*, 2014).

Urbanisation has increased the density and size of cities, increasing the amount of developed land and embodied carbon. The United Nations (2018b) has stated that an estimated 55% of the world's population lives in urban areas and this number is expected to increase to 68% by 2050. The sentiment expressed by the UN shows that this trend will continue into the future leading to increased supply and demand of urban land, energy, water, ecological space, and building materials (Güneralp and Seto, 2012). South Africa's urban population is expected to increase from roughly 67% to 80% by 2050 (Ariyan, 2020). The Department of Rural Development and Land Reform (2019) expressed concerns that urbanisation rates will be focussed in eThekwini, Gauteng, and the Western Cape. Undoubtedly, placing pressure on available resources and ageing municipal infrastructure which affects the sustainability of urban expansion and propagation.

South Africa currently faces a significant unemployment issues, with an unemployment rate of 34.4%, reflecting an increase of 11.1% since 2019 (Statistics South Africa, 2019). By the same token, the Centre for Affordable Housing (CAHF) in Africa (2020a) expressed a similar concern, whereby only 21.15% of South Africans can afford a low income home. Certainly, there is a need for affordable housing and demand for affordable housing will only increase. The supply of affordable housing will help reduce South Africa's inequality gap and improve the wellbeing of low-income earners. Conversely, there is an inadequate supply of housing resulting in economic, political, and social problems for South Africans (Marutlulle, 2021). The lack of affordable homes has forced low-income households to migrate to informal settlements where people are exposed to social stress, violence and unsanitary conditions (Statistics South Africa, 2019). The affordable housing submarket seeks to mitigate this urbanisation pattern, by providing homes to low and middle class income earners within these serviceable areas (CAHF, 2020b). While definitions vary, it generally targets individuals excluded from market-rate or social housing markets. Gan and Hill (2009) identify three key dimensions, 1) purchase, 2) repayment, and 3) income affordability. Supporting this, UN-Habitat (2011) argued that affordability includes acquisition, operation, and sustainability. Therefore this dissertation will pivot the definition of affordable housing on the aim that households should not pay more than 30% of their income towards accommodation expenses (O'Dell *et al.*, 2004; Schwartz and Wilson, 2008; Mota, 2015; PD&R Edge Home, 2017).

The National GHG inventory for South Africa by the Department of Environmental Affairs (2014) indicated that South Africa's residential sector is heavily reliant on electricity to meet its needs. According to the Department of Energy (Department of Energy, 2018), residential buildings consumed approximately 24.39% of South Africa's electricity. Given the substantial electricity demand from residential buildings, it is crucial to consider the source of this electricity, which is predominantly generated from fossil fuels (International Energy Agency, 2020). Baker *et al.* (2015) reported that fossil fuels accounted for 92% of South Africa's power generation. Therefore, the electricity consumed by residential buildings indirectly leads to significant amounts of GHG emissions.

Carbon emissions from buildings occur throughout their life cycle, from material production and construction to operation and demolition. While operational emissions have traditionally received the most attention, studies show that embodied emissions can exceed them (Ibn-Mohammed *et al.*, 2013). Factors such as occupancy patterns, material choices, and construction methods significantly influence a building's carbon profile (Tejero et al., 2018; Minunno et al., 2021). For instance, concrete and steel have higher embodied energy than timber, while prefabrication may reduce emissions (Hannoudi *et al.*, 2024). Geographic context, including climate and local regulations, also plays a role (Lima *et al.*, 2021).

It can be seen from the above analysis that the built environment significantly contributes to GHG emissions. Humans use buildings every day for personal and professional needs, with the main goal to improve their living comfort (Alhorr and Elsarrag, 2013). Therefore, buildings have to respond to their surrounding climate and occupant needs (Alhorr and Elsarrag, 2013). However, this improved living comfort produces significant amounts of GHG emissions through excessive utility use and waste production, resulting from inefficient building designs and techniques (Dikmen and Gültekin, 2011). Therefore, the built environment has significant potential to reduce carbon emissions compared to other industry sectors (United Nations Environment Programme, 2009; Alhorr and Elsarrag, 2013). Multiple studies have shown that improve building materials and energy efficiencies can considerably reduce GHG emissions and improve the sustainability of the built environment (von Paumgartten, 2003; Biwole *et al.*, 2016; Iyer-Raniga, 2019).

Dainty *et al.* (2012) stated that significant advancements within the late 2000's resulted in the shift from traditional construction methods towards a more integrated and dynamic construction approach. Innovations within the housing sector generally took the form of improvements or substitutions of building materials and products (Koebel, 2008). Koebel (2008) further explained that innovative initiatives cover all building elements from the foundations, through to the building's aesthetics. The drive towards (Zeb *et al.*) has been propelled since the late 1990's with Japan implementing net-zero energy solar home incentive programmes and the US Department of Energy implementing an action plan to develop 100,000 net-zero energy solar affordable homes by 2020 (Charron, 2005). Furthermore, Seyfang (2010) argued that innovation goes beyond these traditional viewpoints promoting improved governance, enhanced community engagement and contextualised solutions that fit the parameters of a development.

In this dissertation, ANZEHs are defined as affordable housing that does not create embodied or operational emissions. These are buildings that produce at least as much energy as they consume over the course of a year (Sartori *et al.*, 2012). However, NZEBs have a distinct focus on energy consumption with indirect benefits being expressed across other pillars of sustainability and within the context of economic, social and ecological values (Brundtland, 1987). Given the major role that residential buildings play in energy consumption and GHG emissions, NZEBs are an effective method to optimise energy consumption and reduce the ecological impact of housing (Belussi *et al.*, 2019). The development of ANZEH will support South Africa's net-zero 2050 transition which has been extremely slow and unfruitful (PWC, 2023). PWC (2023) further iterated that Eskom will start decommissioning and repurposing coal power plants to be retrofitted with renewable energy generation and storage, beginning with the removal of 3,600 MW of coal power from the grid. South Africa's climate action tracker indicated that the current policies and targets are insufficient to meet 2030 emission reduction goals because the government policies are not stringent enough and the country's track record for meeting CO_2 goals has been lacklustre (Climate Action Tracker, 2022).

Governments provide building regulations and standards which are a central part to the development of the built environment (Baiche *et al.*, 2006). These regulations and building standards only indicate the minimum energy requirements that must be met (Meijer and Visscher, 2007). Hence, the adoption of ANZEHs has been a slow and/or non-progressive. Despite this critique, governments and organisations are beginning to realise the importance and benefits of ANZEHs through the integration of sustainable development goals (Leininger and Tosun, 2017). Given South Africa’s insufficient 2030 emission targets and minimum energy efficient building regulations, businesses must make net-zero carbon buildings a standard practice despite slow regulation and policy intervention’s by government bodies (Laski and Burrows, 2017).

Paumgartten (2003) argued that the introduction of green rated building systems promoted the development of a sustainable environment, because companies and organisations receive recognition for building sustainably. There are multiple green building rating systems worldwide that are encouraging and mainstreaming the adoption of NZEBs (Alhorr and Elsarrag, 2013; Cole and Jose Valdebenito, 2013). These rating systems encompass green certificates that are internationally recognised such as Leadership in Energy and Environmental Design (LEED) and the Building Research Establishment Environmental Assessment Method (BREEAM), and other more country integrated rating systems such as the Green Building Council of South Africa (GBCSA) Green Star Rating System (von Paumgartten, 2003; Cole and Jose Valdebenito, 2013; Green Building Council of South Africa, 2021). However, these NZEBs tend to be expensive and only cater towards premium grade developments.

South Africa has increasingly embraced green buildings, primarily for financial benefits and to enhance corporate sustainability image. The GBCSA Green Rating System is the predominant green star rating system in the country due to the GBCSA's influence in the built environment sector. Since 2008, the GBCSA has been a leading promoter of sustainability, advocating for and educating about green developments. Despite these efforts, the high cost associated with GBCSA's education and certification for ANZEHs has created a barrier to entry (Coetzee and Brent, 2015). This barrier hampers the research and development necessary for bridging the gap between ANZEHs and developers, thereby slowing progress in this vital area.

In the face of the above criticisms, there remains a gap between the knowledge and understanding that property professionals have regarding ANZEHs. The GBCSA’s and other rating systems with a high barrier to entry has prevented the rapid uptake and investment into sustainable housing, with minimal investment into ANZEHs. Moreover, the need for ANZEHs will reduce the operating costs of affordable housing by reducing the consumption of electricity (Belussi *et al.*, 2019). Thus, resulting in a decreased demand for natural resources and the generation of GHG emissions (D'Agostino and Mazzarella, 2019). At the same time, developers will develop a more holistic understanding of ANZEHs, and the types of initiatives employed to improve the energy efficiency of affordable housing. Bridging the gap between informal, insecure, unsafe housing and formal, dignified and quality housing.

1.3 Problem Statement

South Africa is facing an inadequate housing supply challenge with one-tenth of the nation living in informal settlements (Simbanegavi, 2021). This number is expected to rise as the inequality gap within South Africa increases. Additionally, South Africa is gripped by high unemployment and a growing lower class which has increased the demand for affordable housing. By the same token, the nation has seen a drive towards sustainable buildings which seek to reduce the use of resources and the negative environmental impact of the built environment. This drive has become a pressing concern as governmental policies and regulations are insufficient to meet 2030 net-zero carbon emission goals. Additionally, the country's intermittent electricity supply has been classified as a state of national disaster highlighting the need to reduce grid tied energy demand. Moreover, the cost of electricity has been increasing exponentially making household operations expensive for lower-income families and even unaffordable. Therefore, there is a need for an ANZEH framework to evaluate the sustainability and energy reduction of ANZEH to promote net-zero energy affordable housing and reduce the energy stress on the electrical grid.

1.4 Research Question

The primary research question to be investigated is:

What impact will an affordable net-zero energy house have on the life cycle sustainability of affordable housing in South Africa?

To address the primary research question, the following secondary research questions will be applied:

I. What are the critical success factor mechanisms that underpin an affordable net-zero energy house?
II. How will the selection of building materials, technology innovations, and construction techniques contribute towards achieving an affordable net-zero energy house?

III. What impact will affordable net-zero energy house have on reducing South Africa's life cycle emissions?

1.5 Research Aim

This study aims to evaluate the impact of affordable net-zero energy housing on the environmental life cycle sustainability of free-standing houses in South Africa.

1.6 Research Objectives

The research objectives that will be used to answer the research question are as follows:

- Identify and analyse the critical success factor mechanisms that form the foundation of an affordable net-zero energy house.
- Determine the construction, material, technology and building technique factors that must be considered in achieving affordable net-zero energy houses.
- Evaluate the state and potential influence of the affordable net-zero energy houses on South Africa's life cycle emissions.
- Evaluate the economic life cycle performance of an affordable net-zero energy house in South Africa.

1.7 Overview of Research Methodology

Firstly, fundamental observations and theoretical perceptions were derived from the development of the rationale of the study, research question, aim, objectives, and theoretical framework. Subsequently, the following two-tiered research methodology was employed to develop the research instrument and answer the research question:

A critical literature review of the state of affordable housing and NZEBs against the South African backdrop was undertaken, the elements that underpin NZEBs were identified and examined, and the methods used to analyse the ANZEHs within the local and international context were reviewed. This provided the baseline to identify a list of critical success factors that are practical and achievable within South Africa's built environment. The literature review was used to guide the development of a semi-structured questionnaire to ascertain the impact and challenges of ANZEHs.

Qualitative data in respect to the semi-structured interviews was analysed using content analysis to determine emergent themes and the impact ANZEHs will have on the life cycle sustainability of affordable housing in South Africa. The findings from the interviews guided the modelling of 3 different levels of ANZEHs. The findings from these models were used to determine the influence of varying combinations of construction techniques and building materials.

Conclusions were derived from the research findings and recommendations were made in terms of the findings.

1.8 Scope And Limitations

The scope of this thesis examines the residential housing sector, specifically aimed at assessing the life cycle sustainability of ANZEHs in South Africa. It is important to acknowledge that the researcher’s focus is on the life cycle carbon. which did not encompass an in-depth analysis of social sustainability aspects. The study's scope is confined exclusively to residential buildings within the confines of South Africa and their embodied and operational energy consumption requirements. The prevalence of NZEBs and ANZEHs in the South African context remains relatively low and resulted in limited available knowledge and resources pertaining to ANZEHs within the context of South Africa, thereby influencing the extent and depth of the research findings.

1.9 Dissertation Structure

Chapter 1 introduced the study, presenting the research question, aim, and objectives. It further expressed the limitations and scope of the research.

Chapter 2 provides a literature review of affordable housing in South Africa, followed by the various components of sustainable development. The nexus between affordable housing and sustainability was then discussed. Finally, the carbon life cycle and the emission stages of a house were discussed, and the theoretical framework developed.

Chapter 3 documents the research philosophy and paradigm that guided the study’s data collection and analysis. The chapter further unpacks the mixed method approach used to generate the qualitative findings and quantitative analysis.

Chapter 4 presents the selective codes developed from the qualitative content analysis. The chapter then transitions to the quantitative modelling that unpacks the life cycle carbon emissions (LCCE) and whole life-cycle costs.

Lastly, chapter 5 draws up the study’s conclusions and addresses the research objectives and questions. It further outlines the research’s contribution to knowledge, recommendations and further avenues of research.

2 LITERATURE REVIEW

2.1 Introduction

This chapter starts with an overview of affordable housing delving into its characteristics, challenges and prevalence in South Africa. Attention is then paid to the holistic understanding of sustainability within the built environment, with a focus on affordable housing. Next, South Africa's legislative energy consumption attributes are evaluated to understand the facets that drive the maximum mandatory energy efficient levels within a home. Finaly, the chapter explores and examines the elements and characteristics of an ANZEH.

2.2 Overview of Affordable Housing

2.2.1 Affordable Housing Within an International Context

Housing is recognised as a basic human right under international law, yet more than 1.8 billion people live in informal settlements or inadequate housing (United Nations, 2022). Housing constitutes the fundamental social conditions for citizen wellbeing and quality of life within a nation (Chang *et al.*, 2017). However, rapid urbanisation, housing shortages and inadequate infrastructure is imposing a challenge for low income earners to afford homes (Landman and Plessis, 2002; Dezhi *et al.*, 2016). Consequently, affordable housing has become the main agenda within many developing nations and organisations (Geertman *et al.*, 2015).

Over the past decade, the challenges surrounding housing affordability have intensified due to diminishing land availability, rising development costs, growing populations, and stagnant incomes that fail to keep pace with inflation (Anacker, 2019; Oner, 2020; Echendu and Okafor, 2021). Aini *et al.* (2016) iterated that housing is the most important component of an urban economy, providing the foundation for economic development and growth. Evidence in support of this notion is highlighted by Biron (2013), who stated that high-income countries experience rapid and high levels of urbanisation which supported their economic development. These points illustrate the co-relationship between economic development and urbanisation.

The improved living conditions and income levels associated with urban precincts creates a pull factor that attracts citizens from rural areas (McGranahan and Satterthwaite, 2014). This urban population growth increases the emphasis of adequate housing as more people migrate to urban precincts. An estimated 55.3% of the world's population currently live in urban areas and this number is expected to rise to 60.4% by 2030 (United Nations, 2018a). This urbanisation trend is also driven by population growth, where rapid globalisation has significant impacts on environmental, social, and economic aspects of cities and individuals (Zhang, 2016).

Urban development and the concentration of economic activities increasingly center around financial hubs, shaping the prospects of cities (Zhang, 2016). Bloom *et al.* (2008) argued that the positive benefits derived from cities are a function of the following factors:

1. Cities concentrate citizens, offering diverse labour pools and reduce the proximity between suppliers and consumers.
2. Cities provide improved opportunities for citizens.
3. Companies can respond to market demands more easily and benefit from vertical and horizontal profit spill over.
4. The proximity induced by cities reduce the cost of transportation and decrease the cost of trade. Further, the high-density urban environment serves as a production and service hub increasing the available choices of goods and services.
5. The aggregation of individuals, ideas and education in cities promote innovation and development.

The above passages emphasise the significance of housing within the urban landscape, highlighting the economic benefits that can be realised through strategically located accommodation. However, rapid urbanisation has led to the rise of informal settlements, which have negatively impacted the economic position of low-income residents (Jones Lang LaSalle, 2019). This trend is driven by house prices increasing beyond levels considered affordable which forces low-income earners to city peripheries, where real estate is cheaper, degraded, obsolete and in highly congested areas (Schwartz, 2016; Jones Lang LaSalle, 2019).

For housing supply to increase, the cost of purchasing a house must be higher than the cost to construct it (McGaffin, 2018). However, this is not always the case as households are unable to afford accommodation which prevents ‘increase housing supply’ indicators from informing developers to increase stock. This lack of affordable and adequate housing leads to informal developments which constitutes security and health risks that arise from homelessness (Tshitereke, 2008).

As the lack of housing intensifies, the cost of moving out of informal settlements increases, and constructing new developments becomes more expensive, the affordability and availability of adequate housing will have significant negative economic consequences. These consequences include reduced productivity and social well-being (Tshitereke, 2008).

This housing overview brings attention to the intricate relationship between housing, economic, social, and environmental development which has been extensively explored (Doling *et al.*, 2013; Maclennan *et al.*, 2015; Akpolat and Bakirtas, 2018; Anser *et al.*, 2020; Murshed *et al.*, 2021).

2.2.2 What is Affordable Housing?

The term 'affordable' does not have a clear meaning, and this term is generally vague and applied within the context of a specific situation (McGaffin, 2018). The non-consensus meaning surrounding affordable housing arises from questionable definitions and measures (Abelson, 2009). The literature below highlights the diverse housing affordability definitions and the significant variance between different housing affordability understandings:

- Butcher (2020) indicated that affordable housing valuations range between R300,000 – R600,000.
- CAHF (2020b) indicated that affordable South African housing should range between R300,000 – R600,000.
- Households have an affordability problem when they spend more than a specific percentage of income on adequate housing (Hulchanski, 1995).
- Based on RICS Valuation of land for affordable housing (2nd edition) (2016), affordability was defined using the England National Planning Policy Framework as housing which meets the needs of households who do not have the finances to meet the market.
- The Habitat for Humanity (2021) identified affordable housing as government supplied housing that incorporates social housing.
- In America, affordable housing is measured using an income ratio where the 30% threshold has become the standard (PD&R Edge Home, 2017). This threshold indicates whether households will have enough money for non-discretionary costs.

- In Australia, affordable housing is measured by two methods (Parliament of Australia, 2016):
    - Expenditure ratio which compares household expenditure to income.
    - Residual method which focuses on a household's ability to maintain an acceptable standard of living.
- Sani (2015) noted that affordable housing meets the needs of the low to middle income households in a manner that allows them to meet their basic living costs.

These definitions all express a similar rationale that affordable housing must meet the needs of those who are financially constrained.

Housing affordability is measured in multiple manners, with each one having their own limitations and advantages. These measures include price-to-income ratio, expenditure-to-income ratio, residual income measure, housing quality measure, and subjective measures, which are summarised in the Table 2.1 below. These methods are critical to measure household income affordability and they describe household expenditure, spending trends, inform public policies, and determine criteria for affordable housing (Hulchanski, 1995).

Table 2.1: Types of affordable housing measures

Type of Measure	Example of Indicators	Advantages	Limitations
Price-to-income ratio	House or rent price as a ratio of income	• Simple calculation • Relies on readily available data	• Does not account for interest rates • Does not provide an indication of housing costs
Housing expenditure-to-income ratio	Household expenses as a ratio of disposable income	• Breaks down housing expenditure • Simple to calculate	• Mortgages will make housing options seem unaffordable • Does not indicate the quality of housing
Residual income measures	Income less non-housing needs will indicate available funds for housing	• Indicates income household has left after paying for	• Mortgages can cause misrepresent housing affordability
Housing quality measures	Number of rooms per person	• Assess whether a house or flat is over crowed	• What constitutes satisfactory housing quality differs across individuals
Subjective indicators of housing affordability	Satisfaction of availability, affordability and quality of house.	• Understand the drivers of housing satisfaction • Complements other affordability measures	• Household interpretations and expectations differ across countries and individuals • Households will have a different view of what constitutes affordability

Source: (Meen, 2018; Adema and Plouin, 2021)

The preceding paragraphs and Table 2.1 have highlighted the different affordable housing definitions and the multiple ways affordable housing can be measured. However, it can be deduced that affordable housing is intended for individuals who cannot afford market related prices or do not meet the criteria for social housing. Affordable rents and house prices are generally in between market rates and social housing rates, with no exact figure specifying the price range (Schmid and Silva, 2015). Nevertheless, this understanding is seen as inadequate in relation to the World Economic Forum's definition (2019), where affordability does not only refer to purchasing, operating and maintaining accommodation, but also considers transportation, services and infrastructure. This paradigm arises from a house being affordable to purchase but far from schools, employment opportunities, etc. It cannot be classified as affordable because the household's living expenses will not be sustainable. Gan and Hill (2009) argued that affordable housing comprises of three elements:

1. Purchase affordability which examines the ability of a household to acquire a mortgage bond.
2. Repayment affordability which considers the burden imposed by the mortgage instalments.
3. Income affordability which refers to the ratio between housing price and income.

Evidence in support of this position can be found in the UN-Habitat (2011) report which stated that the cost to purchase a house, associated operating costs and the ability of the household to obtain and service a mortgage are the fundamental components of affordable housing. Pivo (2013) supported these concerns stating that the lower-income households might not have enough disposable income to cover other essential needs, depending on estimates regarding non-housing costs. Despite these criticisms, Kalugina (2016) iterated that affordable housing is commonly understood as a household not spending more than 30% of their income on gross housing expenses such as utilities, rates and taxes, or rent. Therefore this dissertation will pivot the definition of affordable housing on the aim that households should not pay more than 30% of their income towards accommodation expenses (O'Dell *et al.*, 2004; Schwartz and Wilson, 2008; Mota, 2015; PD&R Edge Home, 2017).

2.2.3 Extent of Affordable Housing in South Africa

South Africa is experiencing a severe housing shortage, with approximately 20% of urban households living in informal settlements (Simbanegavi, 2021). The residential property sector makes up the largest proportion of property in South Africa, constituting 89% of all property (CAHF, 2020a). The country's rising population and urbanisation has compounded the housing shortage, challenging both the public and private sector to provide adequate affordable housing (Ganiyu *et al.*, 2017).

Social factors like poverty and a growing unemployment levels are expected to increase, putting pressure on affordable homes. This affordability crisis worsens urban disparities, forcing low-income households, migrants, youth, and the elderly into overcrowded and unsafe living spaces due to their limited affordable options. These groups may be compelled to relocate to areas with limited access to job opportunities, education, healthcare, and green spaces (World Green Building Council, 2023). This has resulted in 'peripheral urbanisation' which creates well-provided, built areas that co-exist with informal settlements within city boundaries (Caldeira, 2017). This places pressure on the government to supply housing and basic services for low-income households who cannot afford adequate housing within a city's serviceable peripherals (Brent *et al.*, 2017). Simbanegavi (2021) highlighted the main challenge of promoting large-scale investment in the affordable housing market is that governments need to provide a regulatory foundation to empower developers. Additionally, access to affordable housing is constrained by the low supply of low-income housing from the private sector (Cirolia and Hoek-Smit, 2019).

South Africa experiences special inequality rooted in the country's unequal land and housing policies imposed by Apartheid (Strauss and Liebenberg, 2014). Under the Apartheid law, housing separation was mandated, which separated white and non-white individuals. These policies marginalised non-white individuals and forced them to live in demarcated areas which were located on the peripherals of cities. These individuals access to housing was restricted under the Apartheid Constitution which prevented them from receiving the same land rights as white South Africans (Van Wyk, 2012). These economically deprived areas, known as Townships, were characterised by poor infrastructure, lack of basic services, and the blooming of informal settlements (Turok, 2012; South African Human Rights Commission, 2020). This led to cities being structured in a manner, illustrated in Figure 2.1, that segmented the population based on the colour of a citizen's skin. This illustrates how non-white individuals were forced to the peripheries of cities where access to jobs and services were restricted.

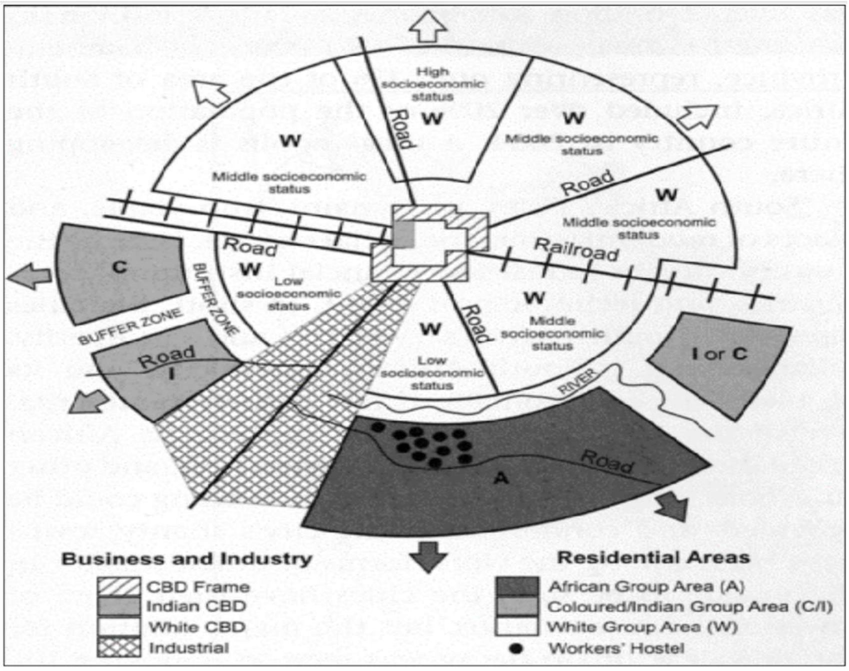


Figure 2.1: Generic apartheid city plan (Davies, 1981)

Following the fall of apartheid, urban renewal projects have been pursued to mitigate the housing and land inequality, infrastructure neglect, and segregation caused by apartheid (Massey, 2020). The legacy of apartheid also led to exorbitant land prices in prime locations, rendering them unaffordable and out of reach for lower-income individuals (Todes and Turok, 2018).

The post-apartheid government has provided low cost housing, however, the implemented supply housing mechanisms have been inadequate at addressing the country's housing needs, observed by the increasing number of informal settlements (Gilbert, 2004). The Department of Human Settlements indicated that there were over 2,700 informal settlements in South Africa with the majority of these settlements being located in unsuitable locations (The Department of Human Settlements, 2022). To solve this housing need, the Department of Human Settlements aimed to deliver 3,000 community residential units and 25,000 affordable rental units over the next few years (The Department of Human Settlements, 2022). The government has also been releasing land to develop affordable housing and infrastructure to service sites, though a site-and-service model. Municipalities have been working with the private sector to fast track municipal land release and support the development of affordable homes (Drummond, 2023). The adoption of new residential development programmes will support economic growth by providing housing in well located areas close to work and amenities such as schools and shops.

The majority of housing programs initiated by the South African government after apartheid have primarily aimed at providing state-subsidised housing to low-income households, with lesser attention given to the lower-middle class (Marais *et al.*, 2020). These projects have often been mismanaged, marked by corruption and poor construction practices, leading to low quality homes being supplied to the venerable lower-class (Tanyi *et al.*, 2016). Tanyi *et al*. (2016) further iterated that these projects are generally poorly located and inadequately sized for a family. Additionally, housing beneficiaries also misuse the houses by either renting or selling them. Nevertheless, all Reconstruction and Development Programme (RDP) and government-subsidised housing initiatives have targeted households at the lowest income levels (i.e., those earning less than R3,500/month) (Rust, 2006). Meanwhile, the private sector has directed its focus towards the higher-income brackets in the market to yield greater investment returns. Consequently, there have been limited affordable housing developments for middle-income households who do not meet RDP or upper market financial requirements and have very few affordable housing options that fit within their budgets (Rust, 2006). There exists a market gap for dignified housing situated in appropriate areas, meeting the specific needs of affordable households who are financial excluded from government programs and who cannot afford market rate accommodation.

2.2.4 Challenges Faced by Affordable Housing in South Africa

South Africa grapples with a multitude of challenges within its housing sector. Among these challenges are prolonged delays in the allocation and release of land for development, escalating construction costs that impede the creation of new housing supply, and a persistent lack of adequate funding, all of which collectively hinder the built environment's ability to address the housing shortage. The burden of operational and maintenance expenses further exacerbates the issue of housing affordability within the country's housing landscape (McGaffin, 2018; World Economic Forum, 2019; Roeland, 2023). The subsequent paragraphs aim to elaborate on these viewpoints to ascertain their contextual significance within the framework of South Africa.

Marutlulle (2021) emphasised that studies have pointed out how constraints in housing supply significantly contribute to inadequate shelter, especially for disadvantaged populations. Butcher (2020) eluded to South Africa's changing residential market with increasing division between housing sub-markets which have a significant impact on the regeneration of neighbourhoods and regional developments. The framework of housing markets will dictate access to housing, value of housing and how income groups are distributed driving the spatial and social housing segregation (Bolt *et al.*, 2010). At the heart of the housing inadequacy issue lies a severe deficiency in available housing units, suggesting an imbalance where the number of individuals surpasses the available dwellings. This is further compounded by the scarcity of land in South Africa, directly contributing to the insufficiency of housing. To address this challenge, the efficient release of appropriately located land for housing purposes is crucial. This strategic approach is essential to meet the required pace of housing delivery and effectively alleviate the challenges associated with housing inadequacy.

Ibrahimu *et al.* (2018) investigated project cost overruns in South Africa and identified several determinants contributing to the increased expenses within the construction domain. These encompassed deficiencies in project planning, volatilities in prices of project materials, elevated interest rates charged by financial institutions, inflationary influences, expenditures on labour, inadequate collaboration among construction entities, ineffective financial oversight, and limited availability of raw materials sourced locally. Surveyed participants indicated that the impact of project location and time wastage on cost escalation within the construction industry was relatively lower when compared to the aforementioned factors.

Moeti (2023) pointed out that the South African government offers subsidies to facilitate first-time homeownership to acquire affordable homes. These subsidies have the capability to mitigate the burden of exorbitant land expenses and escalating costs associated with construction in the housing sector. However, the substantial gap between housing expenses and individual incomes significantly undermines the effectiveness of this initiative. This observation underscores the varying and increasingly unaffordable operational costs associated with housing. Proponents of Barnes *et al.* (2011) and Isalou *et al.* (2014) have questioned whether affordable housing improves living conditions and wellbeing. These authors argued that living in affordable homes will increase a household's spending on utilities and transportation (Barnes *et al.*, 2011; Isalou *et al.*, 2014), effectively reducing the household's standard of living. These incremental expenditures resulting from improved housing has reduced the demand for affordable homes (Charoenkit and Kumar, 2014).

Mulliner *et al.* (2013) argued that financial affordability is not the only method to obtain affordable housing, rather other means can be adopted such as social, environmental and community sustainability. Sustainability initiatives linked to housing design, development location, community development, work opportunities and transport will improve the affordability of homes. At the same time, reducing electricity expenses will improve the financial sustainability of a household considering that electricity contributes about 29.7% of operating costs (MacKillop, 2013; SAPOA, 2022). Property rates consistently surpass inflation rates and significantly contribute to residential operating costs amounting to 52% of gross income (SAPOA, 2022). This clearly indicates that housing has lost its affordability nature. This high operating cost is driven by municipal rates and taxes, and electricity cost increases. Figure 2.2 (below) segments operating costs showing that electricity and property rates contribute the largest proportion of operating costs at 29.7% and 24.9% respectfully (SAPOA, 2022). This suggests that households will need to either reduce their utility usage or switch to alternative forms of energy to lower their operating costs. By doing so, they can increase their disposable income, thereby decreasing the likelihood of defaulting on mortgage payments or rent. This is of importance as SAPOA (2022) has indicated that the residential sector has been experiencing significant increases in bad debts since 2019.

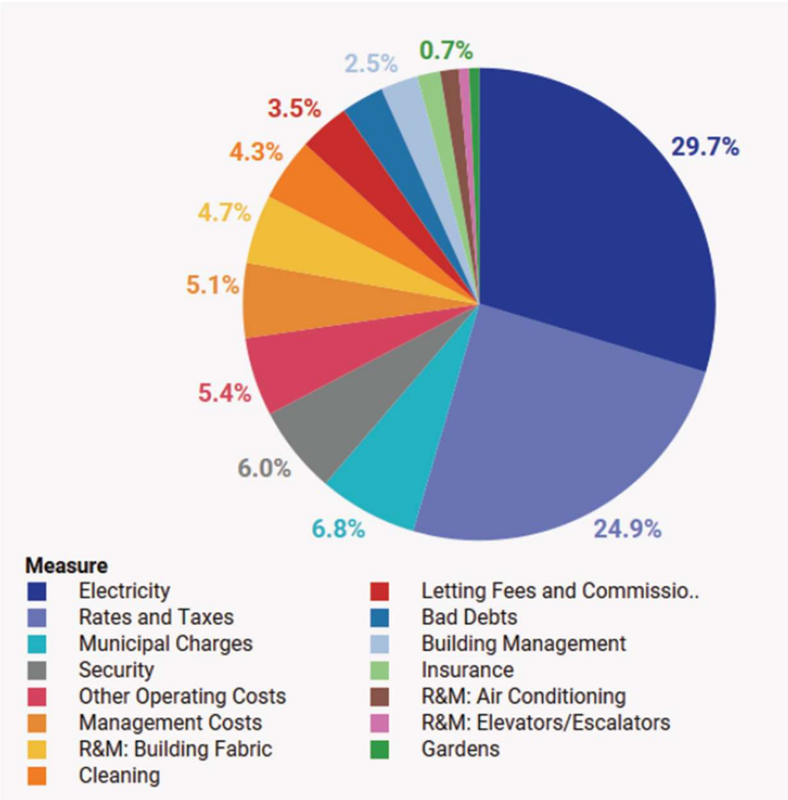


Figure 2.2: Breakdown of total property operating costs by percentage (SAPOA, 2022)

Compounding this affordability pressure is South Africa's exponentially increasing energy crisis and electricity prices, which are putting pressure on households and economic growth. Eskom, which used to be a reliable power generator and distributor, is currently operating at 50% capacity and failing to provide consistent power. This decline in performance is attributed to mismanagement and corruption, causing South Africa's energy crisis and the a 'National State of Disaster: Impact of Severe Electricity Supply Constraints' being issued on the 09 February 2023 (Furchtgott-Roth, 2023; South African Government, 2023a). The country's energy problems haven been growing since 2008 when loadshedding was first implemented with the aim to reduce the grid's energy consumption by 1,000MW for every level increased, and a maximum 8 levels of shedding (8,000MW removed demand from the grid) (Lonwabo, 2022; Statistics South Africa, 2022a). Rolling blackouts put stress on companies because operations have to be halted when their power is cut which has an economic domino effect (Furchtgott-Roth, 2023). The poultry sector is a prime example, where loadshedding increased input costs and reduced the number of chickens being slaughtered, causing a 17% chicken price increase, in 2022 (Gumede, 2023). Not only does this put a strain on the bottom line, but consumers also feel the financial impact with increased grocery prices. Moreover, small businesses are beginning to be liquidated and/or declaring bankruptcy because they cannot take measures to continue operating during loadshedding or finance back-up energy plans (Mahlangu, 2023). Poor economic performance resulting from years of loadshedding has contributed to unemployment steadily increasing, reaching 34.5% as at March 2022 (Africa, 2022). This poor economic performance will only be exacerbated, given that Eskom received approval from the National Energy Regulator of South Africa (NERSA) for tariff hikes of 18.65% in 2023 and 12.74% in 2024, which are lower than the initially requested increments, as reported by BusinessTech (2023). However, these approved increases are in line with Eskom's pattern of electricity tariff rises, averaging 12.19% annually since 2010. This average exceeds the annual CPI index of 4.95% by 7.25%, as reported by Statistics South Africa (2022a). These tariff hikes have been propelled by loadshedding and the incompetency of Eskom, driven by corruption and poor management (Statistics South Africa, 2022a; Furchtgott-Roth, 2023). Even more pressing is Eskom’s decreasing generation capacity driven by aging infrastructure and the poor construction of new power stations (Kenny, 2015; BusinessTech, 2023). The electricity price hikes above inflation have and will further enhance the feasibility of NZEBs, irrespective of the property type. As electricity prices rise, the capacity of ANZEHs to sustain housing affordability will also increase.

ANZEHs hold the potential to alleviate South Africa's energy crisis by reducing energy demand independently of Eskom's need to increase supply. However, this initiative might inadvertently expose South Africa's vulnerable population to worsening energy conditions. As high-income households and businesses increasingly adopt renewable energy solutions, Eskom’s revenue base will decrease impacting the utility provider’s ability to maintain infrastructure and services for lower-income communities who will remain dependent on the grid. While reduced demand will provide operational relief and improve Eskom’s capacity to serve industrial and commercial users, the long-term financial sustainability will be threatened (2Zero50, 2025).

2.3 Sustainability in the Built Environment

The term sustainability was solidified by the Brundtland Report (World Commission on Environment and Development, 1987), which defined it as meeting the needs of today without compromising the needs of future generations. Sustainability within the context of the built environment has become an increasingly important topic, given the exponential rate of urbanisation, the sector consumes the largest amount of resources and generates the most waste (Choguill, 2007; Rogers *et al.*, 2007). Ancell and

Thompson-Fawcett (2008) reiterated that individuals must examine the environmental, cultural, economic, and social needs of current and future generations. Choguill (2007) stated that sustainability is more complex than these definitions infer because applying it to the real world scenarios is a lot more challenging than one might expect. This stems from the broad nature of the term as it is often used in varying circumstances and applied to different industries in diverse contexts (Missimer *et al.*, 2017; Mao *et al.*, 2019). Evidently, researchers have sought to contextualise and define the underlying principles of sustainability which led to the creation of three pillar model (Missimer *et al.*, 2017; Purvis *et al.*, 2019). This model explores and constructs a sustainability framework using an economic, environmental, and social pillar (Giddings *et al.*, 2002). This multidimensional framework should integrate and balance these elements equally, however the framework's equilibrium is not always achieved due to the different sustainability interpretations (Högberg, 2014). Kopfmüller *et al.* (2001) as elucidated by Littig and Grießler (2005), categorised the relationship between the pillars into two main models, namely: the one pillar model and the multi-pillar model.

The one pillar model prioritises the environmental pillar over the other two elements (Littig and Griessler, 2005). This paradigm focuses on the preservation of ecological systems and natural resources required for social and economic activities. However, these social and economic activities are also described as being responsible for environmental harm and must be limited to maintain ecological sustainability (Littig and Griessler, 2005). The more recognised model is the three-pillar model which views the pillars as equal counterparts. This holistic view argues that human needs and activities expand beyond the ecological aspect to incorporate social, economic and cultural elements (Littig and Griessler, 2005). Therefore, the integration of these pillars will prevent the neglect of traditionally undervalued considerations, the inequalities faced within the interpretation of sustainability, and the protection of its functions (Gibson, 2010). The preceding paragraphs will unpack and elaborate on the three pillars of sustainability.

2.3.1 Economic Pillar of Sustainability

Greenland (2019) argued that the economic pillar of sustainability should be viewed within the global context, encompassing business and governmental activities. On the micro scale, economic sustainability is the practice of ensuring one's current consumption levels do not hinder the economic needs of future generations (Högberg, 2014). Mutisya and Yarime (2014) iterated that sustainable economic practices require proficient planning which creates economic prosperity and income generating opportunities. This position is strengthened by Goodland and Daly (1996) who viewed economic sustainability as managing one's capital in a manner that warrants future generational financial growth.

These viewpoints focus on the manufacture, sale, and consumption of resources for continual economic operations in the future. However, Black (2004) highlighted that this pillar also sought to promote and maintain satisfactory standards of living. A sustainable economic system must be adaptive and dynamic enough to shift with environmental, social, and technological changes (Black, 2004).

2.3.2 Social Pillar of Sustainability

Social sustainability is challenging to define due to its diverse nature and unclear definitions. Unsurprisingly, the diverse cultural, social, economic and geographic backdrop of countries makes a generic definition challenging to define. Adding to this challenge, is the dynamic nature of society where social and cultural constructs are consistently changing with continental travel, political factors, and changing social preferences. The built environment's physical features will impact the level and social interaction of individuals and communities (Eizenberg and Jabareen, 2017). Jabareen (2006) correlated social sustainability with urban design principles such as density, greening, transport, city compactness, and mixed use. This perspective is further elaborated by Dempsey *et al.* (2011), who associated social sustainability with adequate housing, a healthy environment, safe neighbourhoods, and ease of accessibility.

However, Eizenberg and Jabareen (2017) argued that the physical aspect of the built environment is not sufficient in tackling neighbourhood challenges, and communities will need to develop social frameworks and processes to achieve social sustainability. Thus, the built environment must provide the foundation for economic development, cultural diversity, social equality, social justice, and social cohesion (Polèse *et al.*, 2000; Ancell and Thompson-Fawcett, 2008). However, Polèse *et al.* (2000) noted that tensions and trade-offs will arise when balancing the social and economic dimensions within an urban environment.

2.3.3 Environmental Pillar of Sustainability

The environmental pillar is a 'recent' concept which took conception with the introduction of the three-pillar model. This understanding introduced environmental practices as an independent concept instead of being understood as a by-product of economic and social development (Moldan *et al.*, 2012). This pillar is often overlooked by consumers and producers, so educators must work on mitigating poor environmental habits (Greenland, 2019; Robinson, 2020).

Environmental sustainability is the use of renewable resources in a way that does not diminish their usefulness for future generations (Moldan *et al.*, 2012). Moldan *et al.* (2012) further iterated that this encompasses the use of non-renewable resources in a manner which does not create a scarcity for future generations, and allows them to smoothly transition to renewable alternatives. Being environmentally sustainable does not only permit the efficient use of resources but also the generation of hazardous materials or pollution which must not exceed harmful levels, and human activities must not create irreversible effects on the ecosystem (OECD Environment Ministers, 2001). These viewpoints are further substantiated by Black (2004), who described the environmental dimension of sustainability as the extent with which ecological systems can continue their essential functions into the future. This encompassed 4 critical aspects, namely: 1) The ecosystem's integrity is upheld and preserved; 2) The biological diversity of an area is maintained; 3) The consumption of renewable resources does not exceed their rate of regeneration; and 4) The rate of pollution emission and waste generation do not exceed the assimilative capacity of the ecological system.

2.4 Understanding Sustainable Development

Sustainable development has recieved increased interest from policy makers, academics, and industry professionals (United Nations, 2015). This uptake has been driven by the 17 sustainable development goals introduced by the United Nations, who have emphasised the increased importance of sustainable operations. The sustainable development goals are characterised as interlinked, integrated, indivisible and universal allowing them to be applied across different nations and environments (Strandenaes, 2017). These goals incorporate all the dimensions of sustainability highlighting the relationships between the economic, environment, and social pillars of sustainability (Glaser, 2012). The interplay between these pillars provides the foundation for sustainable development.

Interconnecting the above discussion, sustainable housing can be expressed as utilising techniques and materials in a manner that promotes environmental, economic, and social sustainable living (Moghayedi *et al.*, 2021). Moghayedi *et al.* (2021) further emphasised that sustainable practices need to be adopted throughout a building's life cycle, starting from the design phase through to the operational phase. Zavadskas *et al*. (2017) stated that sustainable practices must integrate community developments such as schools, hospitals, transport and other amenities to promote a healthy and safe built environment. Hakiminejad *et al.* (2015) noted that policy and legislation shifts towards sustainable urban development will create the framework for efficient and 'green' urban environments. Kaplinski and Ubarte (2016) proposed that integrating multiple-criteria assessment methods will provide a holistic assessment of sustainable developments. This notion is supported by Moghayedi *et al.* (2021), who argued that sustainable critical success factors must be engaged to implement successful sustainable affordable housing.

In contrast to the above, Moghayedi *et al*. (2022) highlighted that South Africa's lack of sustainable building codes, legislation and policies has hindered the adoption of passive building designs, technologies and innovation that promotes sustainable urban environments. This is evident in South Africa's current building codes, SANS 10400-XA (2011), which indicates the minimum building design and energy efficient criteria's that must be met (Zuo and Zhao, 2014). Therefore, this standard specifies the minimum construction requirements for a building to be habitable within the confines of the law. Considering this building code was introduced in 2011, these standards are outdated and to improve the uptake of dated sustainable building designs, energy performance certificates (EPCs) have been introduced (Moghayedi *et al*., 2022). EPCs require the monitoring and public reporting of energy consumption in public buildings and office buildings with a gross lettable area of 1000m^2 or greater, or 2000m^2 or greater, respectively (Department of Mineral Resources and Energy, 2020). This reporting standard does not target residential buildings, however it indicates that legislative policies are beginning to reflect current sustainable practices and requirements to meet a 2050 net-zero carbon emission goal. Therefore, developers must begin integrating sustainable practices and techniques into their developments to future-proof them from stricter sustainable legislation and policies.

2.5 Sustainability Within the Affordable Housing Context

There is no universal definition underpinning sustainable, affordable housing. Many researchers and professionals have tried to define the definition, however their opinions often differ (Saidu and Yeom, 2020). Adabre and Chan (2019) aimed to define sustainable affordable housing by bridging the gap between affordable housing and sustainable development through six critical success factors, namely: 1) developer and government satisfaction; 2) housing operation cost; 3) location of affordable housing; 4) quality of supplied housing; 5) household satisfaction; and, 6) housing demand is met within a timely manner. Similarly, Adabre and Chan (2019) expressed in another paper that policy makers must assist the development of sustainable, affordable housing by enhancing policy reform which caters to developers, household demand, encourages mixed land use, and effective land use planning. Sustainable affordable housing can also be understood as providing and maintaining dignified housing through the preservation of the environment (Sharifzai *et al.*, 2016). The main goal of affordable housing is to be economical for lower-income earners by integrating purchase and future operational housing costs (MacKillop, 2013; CAHF, 2020b). By integrating sustainability initiatives into affordable housing, the cost to obtain and maintain an affordable home will decrease (Mulliner *et al.*, 2013).

Sustainability is usually viewed using the three pillar model: economic, social and environmental (Giddings *et al.*, 2002). The environmental impact will be evaluated against the life cycle of the building and a reduction in energy consumption will reduce GHG emissions (Baker *et al.*, 2015; Ruparathna *et al.*, 2016). From a social pillar perspective, housing provides citizens with shelter, sense of wellbeing and brings communities together (Arman *et al.*, 2009). Kaminsky and Javernick-Will (2015) further evaluated social sustainability as including household sanitation quality which will improve the health of household occupants. Consequently, the reduction in utilities and energy awareness will improve the affordability of housing by reducing utility expenses, contributing to the economic pillar (MacKillop, 2013; Isalou *et al.*, 2014). At the same time, households who manage their finances effectively in the present will prevent future cashflow deficits, preventing them from moving back into their previous housing submarket (Högberg, 2014).

Sustainable affordable housing must be based on these four dimensions of sustainability (Economic, environment, social, and cultural) which influence climate change, the resilience of homes, the economic status of households and their links to the macro economy, social and cultural ties to communities (Badyina and Golubchikov, 2012). Shama and Motlak (2019) understood sustainable development as encompassing multiple facets within social and physical systems such as cultural and social equity, affordability, household health, economics, and neighbourhood environments. In general terms, sustainable affordable developments will promote ecological protection, preserve natural resources, reduce GHG emissions while propagating economic growth over the long term within a community's cultural and social spheres (Shama and Motlak, 2019; Ghaffar and El Aziz, 2021).

The World Green Building Council (2023) highlighted four key elements crucial for the successful adoption of sustainable affordable housing. These elements include:

1. Policy changes involving the integration of sustainable, affordable housing principles into building codes and regulations. This requires enhanced support from national and local governments to enforce, assist, and monitor sustainable affordable housing projects effectively.
2. Improved access to financing through encouraging partnerships, subsidies, incentives, and the acknowledgement by financial institutions of social and environmental impacts in financial products. This approach aims to reduce financing costs.
3. Integration of community participation and collaboration to comprehend community needs and raise sustainability awareness, thereby enhancing the quality of life in neighbourhoods.
4. The implementation of sustainable affordable housing must focus on reducing both embodied and operational energy, prioritise the health and well-being of occupants, as well as promote housing equity.

Numerous challenges persist against affordable housing within South Africa, yet there is an increasing body of evidence demonstrating progress and opportunities. These encompass financial solutions, supportive policies, design strategies, and practical approaches worldwide, enabling the realisation of sustainable, and affordable homes in various regions. The aim is to scale these practices to address the global housing, climate, and health crisis while adhering to fundamental principles of sustainable and affordable housing tailored to specific localities and demographics (World Green Building Council, 2023). At the surface level, affordable housing seeks to be an economic housing option for low-income earners which will prove fruitful when sustainability initiatives are embraced within the affordable housing space. Furthermore, integrating sustainability initiatives into affordable housing will develop stronger communities, promote well-being, and reduce utility consumption.

2.6 Energy Consumption According to South Africa's Building Regulations

South Africa's building codes and structural designs are regulated by the National Building Regulations, which in turn, is governed by the National Building Regulations and Standards Act of 1977 (South African Government, 2023b). South Africa's National Building Regulations (NBR) were created as a set of guidelines and rules for developers to follow when constructing any type of building (SANS, 2023). These standards are laid out in SANS10400 which govern general building principles, structural design, excavations, foundations, external and internal facades, lighting and ventilation, stormwater disposal, fire protection, and energy usage (SANS, 2023). These guidelines are aimed at conventional building designs that utilise concrete floors, brick walls and timber roofing structures, and not traditional construction techniques observed within native South African dwellings (Watermeyer and Milford, 2003).

In 2011 SANS 10400-XA: Energy regulations in buildings were introduced to standardise the minimum energy efficiency of buildings (TIPSASA, 2022). The objective of this regulation was to improve the efficiency level of South African buildings constructed and/or extended after November 2011. In 2021, an updated, more stringent SANS 10400-XA was released that introduces more practical and reasonable energy saving measures (TIPSASA, 2022). This building standard also classified building types and climate zones to allow energy efficient measures to be more targeted. Figure 2.3 and 2.4, below indicated the different building classifications and climate zones. There are 4 routes that a developer can follow to ensure their building will be compliant with SANS 10400-XA (TIPSASA, 2022):

1. The building's rational design by a competent professional, meets or is less than the thermal performance or energy consumption stated by SANS 10400-XA building and zone type.
2. All building elements meet the specified SANS 10400-XA element requirements.
3. The building's calculated thermal performance or energy consumption equals or is less than SANS 10400-XA specifications.
4. The subject building's thermal performance or energy consumption must be equal to or less than a SANS 10400-XA's referenced building.

A1	Entertainment and Public Assembly	F1	Large shop – floor area exceeds 250 m^2
A2	Theatrical and indoor sport	F2	Small shop
A3	Places of instruction	F3	Wholesalers' store
A4	Worship	G1	Offices
C1	Exhibition hall	H1	Hotel
C2	Museum	H2	Dormitory
E1	Place of detention	H3	Domestic residence
E2	Hospital	H4	Dwelling house
E3	Other institutional (residential)	H5	Hospitality
E4	Health care		

Figure 2.3: SANS 10400-XA building type classifications (SANS 10400-XA, 2011)

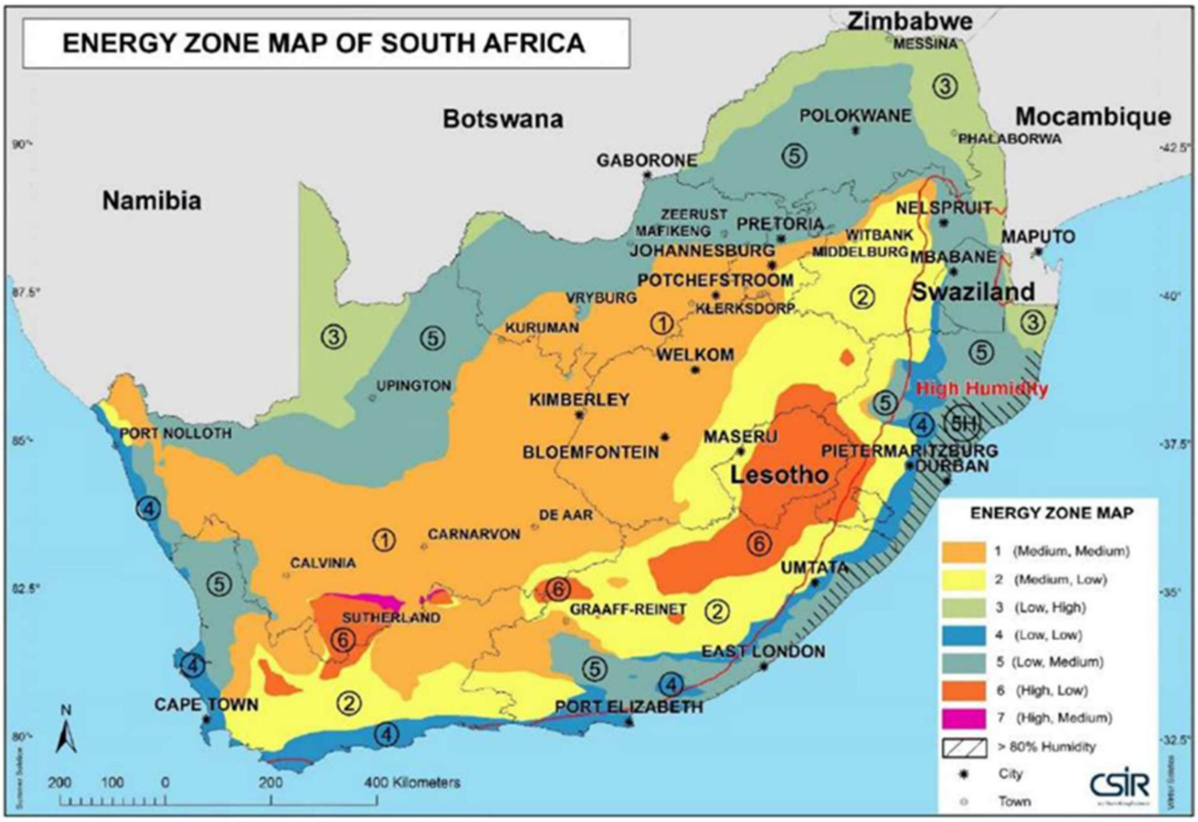


Figure 2.4: SANS 10400-AX energy zone map of South Africa (TIPSASA, 2022)

There are 7 climate zones in South Africa which have been determined by their heating and cooling loads, these energy zones have been summarised in Table 2.4 below. Zone 5 has also been broken down to include a sub-zone '5H' that accounts for the area's high humidity.

Table 2.2: Heating and Cooling Energy Required

Zone	Heating Load	Cooling Load
1	Medium	Medium
2	Medium	Low
3	Low	High
4	Low	Low
5	Low	Medium
6	High	Low
7	High	Medium

Source: (TIPSASA, 2022)

Table 2.5 indicates the maximum energy consumption that a residential house and flat may have in respect to the corresponding climate zone per kilowatt-hour per square meter per annum (kWh/m^2/a) (SABS, 2021).

Table 2.3: Maximum energy consumption of residential units per climate region

Class of Occupancy	Energy Zone (kWh/m^2/a)							
	1	**2**	**3**	**4**	**5**	**5H**	**6**	**7**
H3 Domestic Residence (Flats)	90	100	50	80	85	60	110	110
H4 Dwelling House (Free-standing House)	95	100	50	80	85	60	110	110

Source: (SABS, 2021)

The first step when determining the maximum energy consumption of a new development is to identify the building type and in which province the building will be situated. These two classifications will determine the required R-values that must be met for a building to comply with SANS 10400-XA. The following sections will summarise SANS 10400-XA's building elements and their corresponding thermal performance specifications.

2.6.1 Building Envelope

2.6.1.1 Orientation

Buildings must be orientated to face North, North-East or North-West depending on their location within South Africa to facilitate the maximum solar gain during winter. This specification applies to all energy zones except for zone 5H whose orientation must enable the use of prevailing winds to facilitate natural ventilation (SABS, 2021).

2.6.1.2 Shading

Shading techniques encompass tinted windows, installing shading devices, or adopting fenestration designs. Where fenestration techniques are adopted, the shading device may not protrude less than the factor given in Table 2.6 multiplied by the height. The factor that must be multiplied is determined by the latitude of the development's location.

Table 2.4: Minimum prudence factor of a shading device

Latitude	Multiplier
<= 22	0.33
<= 24	0.36
<=26	0.40
<= 28	0.42
<= 30	0.46
<= 32	0.50
> 32	0.54

Source: (SABS, 2021)

2.6.1.3 Floors

All floors with any form of heating must be insulated underneath with an insulation material with an R-value of at least 1 (SABS, 2021) as indicated in Table 2.7. Suspended exposed floors that form part of the external envelop must be insulated in accordance with Table 2.7. SANS 10400-XA does not stipulate any requirements for other floor types.

Table 2.5: Floor classification and R-value requirements of a floor

Floor Classification & R-value Requirements		
Type	R-value (Equal to or less than)	Energy Zone
Under floor heating	1	All
Suspended floor	1.5	1, 2, 6, 7
	1	3, 4, 5, 5H

Source: (SABS, 2021)

2.6.1.4 External Walls

The revision of SANS10400-XA has seen the introduction of cavity walls due to their improved thermal performance over a half brick wall. However, when cavity walls are exposed to high or low temperature conditions, they will become too cold in winter or too hot in summer. Therefore, these walls can be insulated to exponentially improve their thermal resistance during hot and cold seasons. Table 2.8 below indicates the R-values that an external wall must achieve to meet SANS 10400XA's requirements. In the case where a cavity wall has been insulated, the recommended (Not a mandatory requirement) R-values that should be achieved have been highlighted in Table 2.9.

Table 2.6: Masonry wall R-value requirements

Masonry Wall R-value Requirements		
Type	R-value (Equal to or more than)	Energy Zone
Collar jointed wall, plastered internally	0.4	3, 5, 5H
50mm cavity wall, plastered internally	0.6	1, 2, 4, 6, 7

Source: (SABS, 2021)

Table 2.7: Cavity wall and insulation greater than 50mm R-value requirements

Cavity Wall & >50mm Insulation		
Type of insulation	Recommended R-value	Energy Zone
Expanded polystyrene (EPS)	2.03	All
Mineral Wool	2.12	All
Polyurethane (PU)	2.6	All
Extruded Polystyrene (XPS)	2.26	All

Source: (SABS, 2021)

2.6.1.5 Roof Assembly

SANS 10400-XA makes roof insulation provisions which aims to reduce heat loss through the roof and direct attic heat away from the house. Table 2.10 below indicates the required R-value that a roof assembly must achieve to obtain the minimum thermal resistance. The heat flow direction within the table refers to the general direction that heat must flow during occupation hours to minimise internal environmental heat gain.

Table 2.8: Roof R-value requirements

<table>
<tr><th colspan="9">Roof R-value Requirement</th></tr>
<tr><td>Energy Zone</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>5H</td><td>6</td><td>7</td></tr>
<tr><td>Minimum R-value per m^2.K/W</td><td colspan="4">3.7</td><td>3.7</td><td>2.7</td><td colspan="2">3.7</td></tr>
<tr><td>Heat flow direction</td><td colspan="2">Up</td><td>Up & down</td><td>Up</td><td colspan="2">Down</td><td colspan="2">Up</td></tr>
<tr><td>Minimum R-value of roof/ceiling insulation</td><td colspan="2">0.30-0.35</td><td>0.30-0.35</td><td>0.30-0.35</td><td colspan="2">0.36-0.48</td><td colspan="2">0.30-0.35</td></tr>
</table>

Source: (SABS, 2021)

2.6.1.6 Building Sealing

Buildings must be designed to minimise air leakage and infiltration at any opening in the external façade.

2.6.2 Building Services

2.6.2.1 Hot Water Supply

SANS 10400-XA piping insulation states that all piping utilised for hot water distribution or heating must be insulated with an R-value material in accordance with Table 2.11.

Table 2.9: Hot water piping insulation R-value requirements

Pipe Insulation	
Piping Diameter	Minimum R-value
<= 80	1
>80	1.5

Source: (SABS, 2021)

2.6.2.2 Lighting

All H3 and H4 occupancies must use light emitting diodes (LEDs) and compact fluorescent lamps or any other lighting technology whose energy demand does not exceed 4W/m^2. Occupancy and daylight sensors must be installed in a manner that no sensor services an area greater than 100m^2.

2.7 Affordable Net-zero Energy House

Many countries around the world have been encouraging improved energy efficient developments with greater on-site renewable energy generation which has created particular interest in NZEBs. A NZEB, also referred to as a zero-energy building, is a building with a total annual consumed energy equal to the amount of renewable energy generated on-site, or consumed off-site renewable energy (Teja, 2018). Crawley *et al.* (2006) emphasised that investor intentions, project goals, environmental impact, and energy costs influence the NZEBs definition. On the back of this, the authors proposed four different definitions, namely: 1) On-site ZEB; 2) source ZEB; 3) cost ZEB; and 4) emission ZEB, each definition proposing its own advantages and disadvantages. Evidently, NZEBs provide an opportunity to reduce both the generation of GHG emissions and grid tied energy usage through high building energy performance and renewable energy generation. NZEBs do occasionally consume non-renewable energy and produce GHG emissions, but their ability to produce excess renewable energy will offset the non-renewable energy consumption. NZEBs are critiqued with only addressing the operational phase of a building while the embodied energy is neglected (Nydahl *et al.*, 2019). This is most likely due to the absence of data, challenges quantifying incorporated energy, and the construction industry's hesitance to adopt new construction techniques (Qarout, 2017).

Advances in renewable energy generation, construction techniques and research within the NZEB space has created detailed energy performance reports comparing conventional and NZEB designs, and detailing design efficiencies (Teja, 2018). NZEBs are underlined by three main energy efficiency measures, namely: 1) passive design; 2) service system; and, 3) power generation (Deng *et al.*, 2014). A superior passive design will incorporate thermal insulation, building orientation, effective overhangs to reduce thermal and electricity loads. These load reductions are further reduced with energy efficient lighting, optimised heating, ventilation, and air-conditioning monitoring systems. In their paper on energy consumption and household energy usage behaviour, Cui *et al.* (2017) noted that high appliance prices was the primary hindrance to acquiring high-efficiency appliances. Moreover, households showed scepticism about the ability of these products to save energy. This scepticism arose because the energy-efficient products' effectiveness is significantly impacted by individual energy-consuming behaviours, resulting in inconsistent energy-saving outcomes. This indicates that household behaviours and perceptions will significantly influence the reduction of energy consumption habits which minimise electricity usage. A household could fail to achieve net-zero energy status due to being a high energy user, whereas another household, characterised by lower energy consumption habits, could effectively render the same house a net-zero energy home. Renewable energy solutions such as solar, wind, and biogas will provide carbon emission free energy source. The evolution and widespread adoption of NZEBs will transform these solutions into a practical approach for curbing energy consumption and enhancing energy resilience within the built environment. (Marszal *et al.*, 2011). Livingood *et al.* (2016) motioned that the potentials of scaling zero energy buildings will create an opportunity for localised electrical grids that will utilise grid load diversity to share renewable energy, enhancing the ability of developers and policy makers to adopt NZEBs and develop net-zero energy neighbourhoods.

On the other hand, the upfront carbon rating attributable to the construction of the building, is generally overlooked and remains constant for the building's life cycle. Therefore, the proportion of embodied carbon increases as energy efficiencies improve, and can range from between 9% (Conventional building) - 70% (Nearly zero energy building) of a building's total emissions (Chastas *et al.*, 2018). Extensive research has been conducted to explore various strategies for reducing the embodied carbon of buildings. Akbarnazhad and Xiao (2017) broadly categorised these embodied reduction strategies into five groupings, namely: 1) The use of low-carbon materials involves selecting alternatives based on their carbon footprint by considering factors like raw material type, location, extraction and processing methods; 2) Reduce the required material to construct a home which will directly lower embodied carbon through optimised design and waste minimisation during manufacturing and construction; 3) Reuse and recycle materials during construction and at the end of building life to preserve embodied carbon by reducing emissions from demolition and landfilling; 4) Source local materials to reduce transport emissions; and, 5) Adopting construction optimisation strategies to minimise carbon emissions during construction by optimising equipment operations and improve construction site layout to reduce on-site transport emissions. These categories are further substantiated by Moncaster and Pomponi (2016), who also included government regulations and policies to guide developers and homeowners towards greener alternatives.

Benchmarking provides performance targets for evaluating the feasibility and impact of NZEBs, in terms of energy consumption, on-site generation, and storage. Internationally, standards such as the UK Net Zero Carbon Buildings Standard offer measurable thresholds for carbon emissions limits and targets, promoting efficient designs, energy saving technologies, and renewable energy (Standard, 2025). Although, the UK standard primarily focuses on carbon emissions, its emphasis on reducing emissions and maximising renewable energy aligns closely with NZEB principles. Complementary rating systems such as BREEAM and EDGE further institutionalize benchmarks for sustainability, covering both energy efficiency and life-cycle carbon performance (LEED, 2021; BREEAM, 2023). While this study concentrates on the energy impact of ANZEBs, the results may be compared to these standards to reflect the broader implications of decarbonisation.

Green and sustainable rating tools were developed to promote and measure the design, construction, and operation of buildings in a sustainable manner (Ade and Rehm, 2020). Ade and Rehm (2020) stated that these systems aim to develop a holistic, sustainable view with overlapping structures and assessment methods. This approach considers multiple environmental factors while addressing practical market demands. Despite this criticism, green rating tools have propelled the built environments sustainability sentiment and awareness amongst professionals (Griffiths *et al.*, 2020).

South Africa's leading green rating tools, established by the GBCSA, who is an affiliate of the World Green Building Council, were developed based on Australia's rating system and selected due to the countries' comparable climates (Illankoon *et al.*, 2019). In addition to these tools, the construction industry in SA has embraced other rating systems like Edge and South African National Standards (SANS) 10400-X and 10400-XA (Swift, 2013; GBCSA, 2023). These tools seek to help developers benchmark and evaluate energy and carbon performance of South African buildings.

Given the above, there is a strong distinction between embodied and operational carbon emissions outline by Ibn-Mohammed *et al.* (2013) and expressed below. Figure 2.5 presents a graphical representation of a building’s life cycle where embodied and operational carbon is accumulated. Embodied carbon is influenced by the materials used to construct a house and is largely determined by the type of materials used, construction techniques, material sources, and the efficiency of manufacturing processes to produce construction materials. Almost all embodied emissions are incurred during the initial construction stage of a building, with the remainder occurring during maintenance and renovation. Reducing embodied carbon can be achieved by optimising the building’s fabric to minimise material use, or by intelligently specifying and selecting materials with lower embodied carbon and energy intensity. While operational carbon refers to the energy required to sustain indoor environmental conditions and support the day-to-day energy requirements, through processes such as heating, cooling, lighting, appliances, ventilation, and air conditioning. Operational emissions accumulate over time and can be influenced throughout the building's life. Reducing operational energy consumption can be achieved more effectively using energy-efficient appliances, renewable energy technologies, and advanced insulating materials, which are increasingly available.

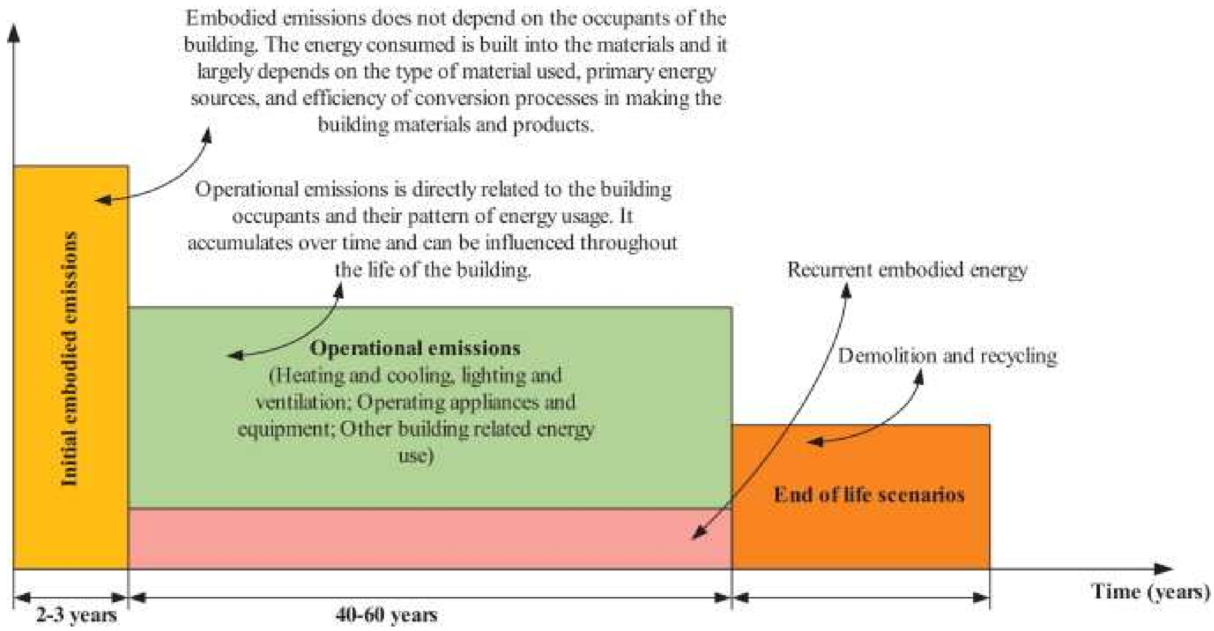


Figure 2.5: Life cycle carbon emission breakdown (Ibn-Mohammed et al., 2013)

Affordable housing was described in Chapter 2.2.2, as a household that does not spend more than 30% of their gross income towards accommodation, and NZEB will minimise the consumption of carbon emission energy. ANZEHs seeks to merge these two constructs to create a home that will consume a net-zero energy ratio while remaining cost effective. The affordability of an ANZEH will depend on optimal design patterns and utilising energy saving technology in a cost-effective manner. D'Agostino and Parker (2018) argued that optimising a NZEB design will allow costs to be re-distributed to more impactful elements allowing the cost of other elements to be reduced. The authors further noted that as the passive design improves and the thermal comfort increases, the incremental cost of more efficient heat and cooling equipment reduces (D'Agostino and Parker, 2018). This observation indicates the ANZEB designs must articulate their budgets effectively to redirect cashflows towards high carbon and energy performance building elements and technologies in order to maximise carbon reductions with limited funds. The mature nature of passive designs arises due to the standardisation of simulation software that mimics heat and energy loads in a timely and cost effective manner (Deng *et al.*, 2014). Designers and engineers should adopt these computer models to make significant building changes before construction to optimise their ANZEH, reducing capital costs, delays and overruns. A critical part of an ANZEH will be the installation of photovoltaic (PV) systems to supplement and/or replace grid tied energy, potentially creating an additional revenue source if PV energy is fed into the grid, highlighting that a PV system will not only reduce carbon emissions, but improve the viability of an ANZEH.

Evidently, developers will have to balance the relationship between energy and carbon efficiencies and building costs to achieve an ANZEH.

2.7.1 ANZEB Design Techniques, Features, and Technologies

The following ANZEH dimensions presented below were identified as the foundational elements that underpin the ANZEH critical success factors outlined in the literature review. Figure 2.6 below summarises the expressed dimensions before the proceeding sub-sections unpack these 4 NZEB characteristics to determine which building elements will be suitable for an ANZEH. The diagram indicates the 4 key characteristics of NZEBs.

1) The technical dimension describes the physical housing features, passive energy efficient designs, building layout, alternative materials, and construction techniques which will help reduce the environmental impact of housing (Biyik *et al.*, 2017; Chen *et al.*, 2017).

2) The social dimension describes curtailment and environmental relevant behaviour (Never *et al.*, 2022), and green finance and renewable energy policies (Anser *et al.*, 2023).

3) The environmental dimension focuses on renewable energy production and the use or renewable or recycled building materials (Wells *et al.*, 2018; Wu and Skye, 2021).

4) The economic dimension, highlights high energy efficient technologies and appliances that will reduce a household's energy demanded (Deng *et al.*, 2014).

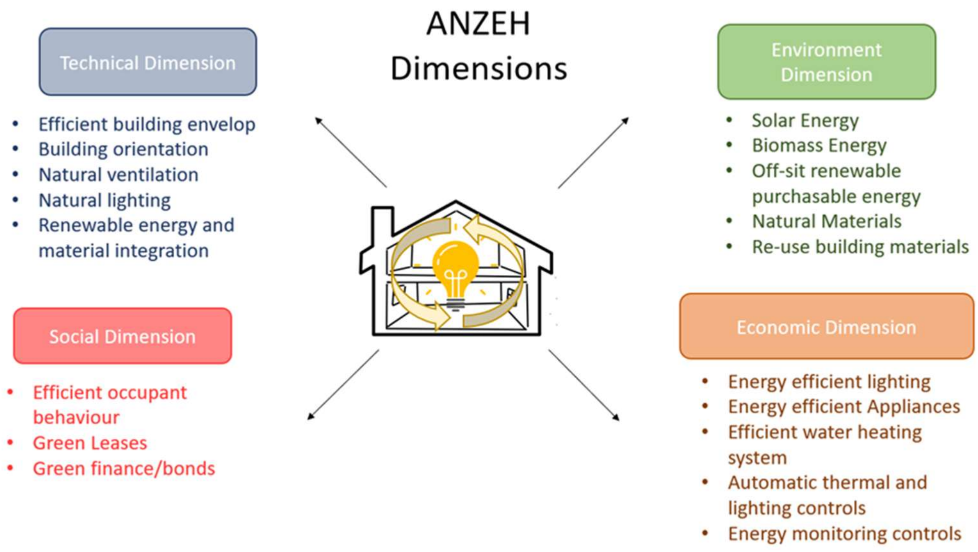


Figure 2.6: ANZEH dimensions

2.7.1.1 Technical Dimension

The technical dimension describes the physical housing features, passive energy efficient designs, building layout, materials, and construction techniques which will help reduce the environmental impact of housing (Chen *et al.*, 2017). An optimal passive design can improve indoor environmental quality while reducing daylight heating and lighting loads (Gong *et al.*, 2012). Optimal designs can minimise the quantity of building materials to erect a home, simplify construction techniques to reduce on-site emissions, and integrate existing building material into new developments will significantly reduce material consumption (Hestnes and Sartori, 2007; Sev, 2009). Designs should also seek to adopt pre-fabricated elements to allow for efficient transportation, reduced installation time and limited waste production during construction (Hannoudi *et al.*, 2024). Energy efficient design optimisation will support developers and engineers in designing buildings with improved embodied and operational energy performance levels (Shi *et al.*, 2016).

The shape of a building significantly impacts the amount of solar radiation received during the day and heat loss during the night (Mingfang, 2002). A building's design should aim to reduce the ratio between the external façade and construction volume to suit its hemisphere (Aksoy and Inalli, 2006). Building shape should be viewed in combination with building orientation as the angle of the building's position relative to the sun will impact the level of direct insulation, consequently impacting the optimal external façade and construction volume ratio (Aksoy and Inalli, 2006). In the Southern hemisphere, the northern side of a building will receive the highest levels of solar radiation, while the northern side receives the least. Subsequently, a North facing building is considered the optimal design orientation receiving the maximum level of solar radiation during winter. Building orientation will also impact other design elements, such as window-to-wall ratio, shading and PV systems.

The external façade can be considered one of the most important passive design components because it separates external environment conditions from the internal climate. The building element combines insulation, widow-to-wall ratio, glazing and shading techniques to optimise heat gain and loss (Pacheco *et al.*, 2012; Wang *et al.*, 2021). External façade materials and typology designs were the most influential method to reduce capital costs and embodied carbon through the integration of re-cycled materials (Cortesão *et al.*, 2023). Installation and maintenance carbon can be reduced by adopting ease of assembly and disassembly module designs.

Wang *et al.* (2021) indicated that an optimal external façade will alleviate most indoor thermal discomfort as direct insulation will be minimised and thermal insulation improved. Insulating and/or utilising cavity walls in the external façade will minimise heat gain, reducing cooling load energy (Bekkouche *et al.*, 2013). Fantucci and Serra (2019) observed that the use of reflective paint will reduce heat gains between 10%-53% as less insolation is absorbed. Windows are a critical design element for any building providing natural light inlets and exterior views, however, they are responsible for wasting 20%-40% of a building's energy (Jung *et al.*, 2013). Jung *et al.* (2013) further iterated that a window's thermal performance is driven by airtightness, window solar glazing, and thermal transmittance. Window glazing will impact the amount of natural light that will penetrate a building's interior reducing lighting loads, but increase heat loads (Aguilar-Santana *et al.*, 2020). Aguiler-Santana *et al.* (2020) further indicated that window pane thickness will not improve thermal insulation and tinted windows will only reduce light transfer without reducing heat gain. Therefore, double or multi glazed windows should be utilised to maintain suitable natural lighting and low heat transfer rates. Façade overhangs will prevent windows from transmitting undesired insolation which will impact building heating loads (Omrany and Marsono, 2016). Extending external shading overhangs have rapid diminishing returns indicating that their design parameters are constrained. Cheung *et al.* (2005) noted that building simulations indicated that a 100kWh annual saving will be obtained from the first 500mm shading overhang and only an additional 109kWh annual saving is achieved when the overhang is extended by 1000mm. This indicates that developers can standardise shading overhangs reducing design costs and timelines.

In South Africa, housing air-conditioning units and HVAC systems are not widely utilised due to their energy intensive nature. Therefore, integrating natural ventilation into a house/apartment design will significantly improve indoor conditions. The efficiency of natural ventilation is impacted by temperature changes, the vertical hight difference between inlet and outlet stacks, building design, orientation, size, window-to-wall ratio and window-to-floor ratios (Aflaki *et al.*, 2015). Natural ventilation systems will improve the efficiencies of HVAC systems, stabilise indoor temperature levels and provide a temperature energy saving mechanism (Zhang *et al.*, 2021). Adopting wind catchers into a building's design will enhance natural ventilation and cost significantly less than conventional ventilation systems (Jomehzadeh *et al.*, 2020; Patel, 2021).

Proponents of Moghayedi *et al.* (2024) observed that 3D-printing construction methods, play a crucial role in enhancing the sustainability of homes. These technologies offer significant reductions in construction time, carbon emissions, and material wastage, making them viable options for addressing the housing crisis in Africa. The study indicated that 3D-printing has the potential to reduce a home's carbon footprint by 48%, however the initial cost of the 3D-technology is not offset by savings achieved through the reduced construction time. Alternatively, developments can adopt innovative prefabricated construction methods which enhance a buildings sustainability performance beyond conventional building techniques (Moghayedi and Awuzie, 2023). Housing stakeholders should adopt prefabrication techniques including monolithic systems and other prefabricated approaches. These methods should incorporate a significant proportion of local and natural materials to enhance affordable housing projects in local areas (Moghayedi and Awuzie, 2023).

Incorporating sustainable design techniques, such as passive design, the use of recycled and local materials, and energy-efficient systems, will improve the sustainability performance of affordable housing (Moghayedi *et al.*, 2023). These techniques must embrace the entire life cycle, incorporating the climate zone and geographic location into the design. This design approach is referred to as the SIAH-Liveable House which allows stakeholders to modify their home using a modular design to accommodate changing needs without needing to move.

2.7.1.2 Social Dimension

The social dimension seeks to improve awareness and leverage household curtailment and environmental initiatives. Improved levels of household carbon footprints will promote household energy conservation through awareness, tenant behaviour and the purchasing of energy efficient appliances (Never *et al.*, 2022). Steg (2008) argued that a household's energy use is driven by the inadequate knowledge of ways to diminish electricity usage, the high cost and moderate priority to save energy, and the subsequent lack of cost-effective energy saving alternatives. Salom *et al.* (2018) iterated that occupant behaviour and the number of occupants will impact the level of energy consumption, and whether a building, given its renewable generation, will achieve NZEB levels. There are two typical strategies implemented to encourage energy saving behaviour. Psychological strategies seek to educate, and change household perceptions and norms affiliated with energy conservation. Structural strategies seek to change the environment in which energy conservation decisions and actions are made to promote the adoption of energy saving initiatives (Steg, 2008).

Psychological strategies can be promoted through green leases which are rental agreements where the tenant and landlord commit and encourage water/energy conservation and reduced waste generation (Green Building Alliance, 2022). The Better Buildings Partnership (2013) defined a green lease as a standard lease with additional environmental performance clauses that the tenant and landlord must uphold within the context of the property where the tenant resides. The literature has extensively examined green leases within the context of commercial and retail property, however the residential sector has been neglected. This being the case, elements of commercial and retail green leases can be easily converted to residential lease. For example, tenants may only purchase and use energy efficient appliances, or the landlord must make recycling amenities easily accessible to tenants. ANZEH may have the infrastructure and technology to achieve net-zero energy consumption, but this does not mean net-zero energy benefits will filter down to the tenant. Therefore, developers must utilise green leases to encourage energy saving behaviour amongst tenants or mandate that only energy efficient appliances may be used (Collins, 2019).

Anser *et al.* (2023) iterated that green finance and renewable energy policies will enhance access to electricity and boost energy security. These policies and financing incentives will propagate innovation amongst developers making renewable energies abundant within ANZEHs. Green financing will be achieved through green bonds or sustainability-link loans (Duffy *et al.*, 2020). Green bonds are structured similar to conventional loans, except the loan proceeds are allocated directly towards green projects and tracked (OECD, 2016). Sustainability-linked loans are linked to GHG emission goals or sustainability targets. Therefore, the proceeds do not have to be directly invested in green projects, and if the sustainability targets are met, the loan's interest rate is reduced as a reward (Kölbel and Lambillon, 2023). Green finance will promote ANZEH by attaching sustainable criteria goals to loans which are often discounted in relation to conventional loans or bonds, improving viability studies and increasing ANZEH supply.

Local materials should be sourced to reduce the environmental impact associated with the transportation of building materials, such as carbon emissions and fuel consumption. Additionally, employing these strategies will provide substantial benefits to local communities and economies by creating jobs, supporting local businesses, and fostering economic resilience. By prioritising locally sourced materials, construction projects can contribute to sustainable development goals, ensuring that the environmental, social, and economic aspects of sustainability are addressed in a holistic manner (Pomponi and Moncaster, 2016).

2.7.1.3 Environmental Dimension

The environmental dimension focuses on and the efficient use of materials to minimise embodied energy, and renewable energy production. Developers should source alternative low carbon emission materials, such as wood or bamboo, and materials that have re-cycled elements integrated into them. The use of recycled materials can expand to reclaimed materials or the use of demolition materials to enhance resource management (Sev, 2009). Using Pareto's analysis Perera and Victoria (2018) identified that a structure's frame, substructure, external walls, services and upper floors should be given design priority because they contribute the most embodied carbon. Using re-cycled steel and concrete, pre-used materials, alternative low carbon materials, lighter pre-fabricated elements will reduce these high embodied carbon contributing elements (Perera and Victoria, 2018).

The replacement and/or offset of fossil fuel energy will be achieved through the on-site production of renewables, purchasing of off-site renewables, or excess renewable energy being feedback into the grid will outweigh the consumption of fossil fuel energy (Wells *et al.*, 2018; Wu and Skye, 2021). PV systems have been widely adopted by the residential sector due to its simpler installation methods and promising capital investments (Kumar *et al.*, 2020), and South Africa's climate is extremely suitable for solar as it boasts an average of 2500h hours of sunshine annually (Alexander, 2023). Gouveia *et al.* (2020) iterated that other renewable energy sources (e.g. Wind or geothermal) are used less often because their environmental impact (e.g. noise) or capital/maintenance costs are higher. However, these systems come at a higher embodied carbon cost, with solar homes requiring approximately twice the embodied energy of a conventional home due to its technological needs, but it simultaneously reduces total operational energy demand by half over a 50-year lifespan (Hestnes and Sartori, 2007). This highlights that solutions will have to embrace a higher embodied carbon input to offset a larger operational energy footprint.

Renewable energy generation is erratic, heavily reliant on climatic conditions, and impacted by day/night cycles and the weather. To maintain a reliable source of renewable energy, energy storage systems must be considered when designing an ANZEH (Gouveia *et al.*, 2020). For a residential building there are two main forms of energy, electrical energy to run appliances and lights, and thermal energy to heat water (Biyik *et al.*, 2017). There are various available battery options for electrical storage systems such as lithium-ion or lead-acid batteries (Hesse *et al.*, 2017). Where the capital cost for batteries is exceeded or the allocated budget does not cater for batteries, renewable generated energy can be fed back into the grid to offset grid tied fossil fuel generated power. The use of batteries to reduce power fluctuations and store excess renewable energy will enhance an ANZEHs ability to achieve zero operational energy emissions (Yamchi *et al.*, 2019).

2.7.1.4 Economic Dimension

The economic dimension, highlights high energy efficient technologies and appliances that will reduce a household’s energy demand (Deng *et al.*, 2014), effectively reducing the stress on the amount of renewable energy required to sustain a household’s energy habits and operational costs. Implementing electrical smart meters will provide households with the ability to monitor their energy usage in real time (Zheng *et al.*, 2013). Moreover, the increased household energy usage awareness will promote energy behaviours and allow households to track their consumption against benchmarks to determine if they are consuming more or less energy (D’Oca *et al.*, 2014).

Lighting energy consumption has been steadily increasing due to the growing trend of installing more light fixtures in a home. The adoption of LEDs in favour of florescent or incandescent light bulbs has helped curved this increasing energy demand (Cheung and Davies, 2017). LEDs also provide other benefits such as improved lifespan and reduced maintenance costs, however their installation costs are generally higher (Nardelli *et al.*, 2017). Despite this higher installation costs, LEDs are about 80% - 90% more efficient than incandescent light bulbs, therefore the higher capital cost of LEDs are easily recovered over their operational life (Schleich *et al.*, 2014).

The South African government has implemented personal and company solar tax incentives to promote renewable energy installations. Individuals who pay income tax, can claim a tax rebate of 25% of the cost of new PV installations to the maximum value of R15,000 (National Treasury, 2023). While companies may apply for a Section 12B and 12U tax allowance which will allow for accelerated capital depreciation on renewable energy generating assets (Cliffe Dekker Hofmyer, 2021). In the case that the cost of the PV system exceeds the allocated capital budget, a solar subscription service can be utilised which will allow a third party service provider to install a PV system at no additional capital cost and only a subscription cost will be charged on a monthly basis (gosolar, 2023).

Conlon *et al.* (2021) noted that appliances such as refrigerators, dishwashers, and hot water systems can be energy efficient while also being cost-effective. This observation is critical when the number and use of appliances has steadily increased since 2000, despite this criticism, the increase in energy consumption has increased less than the increase in appliances (Patel and Chugan, 2013). The application of electric energy management systems will provide enhanced appliance optimisation and scheduling to optimally utilise renewable energy and reduce the consumption of fossil fuel grid energy. Electricity energy management systems will shift electrical load scheduling and direct energy flows to reduce peak household energy consumption and improve the exploitation of renewable energy (Tsioumas *et al.*, 2018). This system will greatly improve the energy efficiencies of air source heat pumps by optimising run times during the day when plentiful renewable energy is available. Air source heat pumps (ASHPs) are 50%-70% more efficient than conventional geysers with a co-efficient of performance ranging at around 3.75 (Wang *et al.*, 2020). Meyer *et al.* (2019) quantified ASHP within the South African climate and determined that conventional hot water geysers should be retrofitted with ASHPs. Energy savings of more than 50% is achieved depending on seasonal conditions highlighting ASHPs high co-efficient of performance in South Africa’s climate.

These dimensions serve as key pillars in guiding the successful implementation and adoption of ANZEH principles in South Africa. By addressing these dimensions, stakeholders can better understand the essential factors that contribute to the effective integration of sustainability, energy efficiency, and carbon reduction in housing projects. Each dimension highlights a specific area of focus that is crucial for achieving the desired environmental, economic, and social outcomes associated with ANZEH. These are best captured through critical success factors, which are the essential areas of activity that must be addressed to ensure the successful delivery of ANZEHs. The critical success factors for ANZEH were derived from the four dimensions identified in the above sections. Each dimension underpins specific critical success factors that contribute to lowering energy and carbon emissions while maintaining affordability. Table 2.12 provides a summary of the critical success factors for ANZEH by categorising their technical and performance aspects. The ‘Dimension’ heading lists the foundational categories that are critical to achieve an ANZEH, providing a structured overview of ANZEH strategies. The ‘Element’ heading identifies features or design aspects into actionable components. Each element is further broken down under ‘Technical Specification’, which outlines the specific requirements, design characteristics or actions, offering a practical implementation reference point. The ‘Description’ explains the purpose and function of each technical specification. The ‘Impact’ summarises the expected effect of each specification on the building's energy performance. Finally, the ‘Performance Rating’ sought to quantify each specification’s performance ability.

Table 2.10: Summary of ANZEH critical success factors

Dimension	Element	Technical Specification	Description	Impact	Performance Rating
Technical	Passive Design	Orientation	The direction the house is facing.	In the Southern Hemisphere, buildings should be North facing to increase the solar energy gains.	35% energy saving per annum (Albatayneh *et al.*, 2018).
		Shape	Is the house a rectangle, square, etc.	A low-rise building will increase solar gain while reduce thermal heat loss.	Low-rise and non-compact building offers the best thermal performance (Ordoñez *et al.*, 2014).
		Wall-to-window ratio	Amount of window area relative to the amount of exterior wall.	↑ or ↓ house's thermal gain based on desired outcome.	Dependent on window to wall ratio.
		External wall insulation	Material used to improve the thermal performance of the exterior wall.	Reduce thermal heat gain during the day and heat loss during the night,	External cavity wall must have an R-value of 0.6 or greater (SABS, 2021).
		Roof insulation	Material laid on the ceiling to improve ceiling thermal performance.	Prevent thermal heat gain during the day and heat loss at night.	The roof must achieve an R-value of 3.7 or greater (SABS, 2021).
		Glazed windows	Layers of glass separated by a gap for a glazed finished.	Reduce heat gain during the day and heat loss during the night through external windows.	Window's R-value must be greater than 1 (Mann, 2021).
		Façade overhangs/ eave/shading techniques	Portion of the roof or other material that protrudes from the side of a building.	Reduce the amount of sunlight that enters a building during the day.	18% energy saving can be achieved from installing 1m overhangs (Kazem *et al.*, 2022).
		Natural lighting	Any technique used to direct sunlight into a building.	Provides natural light during the day to reduce the reliance on artificial light.	Electrical lighting savings between 10%-30% (Acosta *et al.*, 2016).
		Natural ventilation	The process of creating air flow within a building without using any mechanical system.	Passively cools a house, reducing energy required for air conditioning.	Cooling energy consumption savings between 8%-78% depending on the weather and air quality (Tong *et al.*, 2016).
Social	Psychological strategies	Green citizen	Teach house occupants about energy conservation.	Households will actively reduce their energy consumption.	Energy conservation is a function of household's proactive ability to reduce consumption.
		House manual	Information booklet which explains the objectives of the house and effectively utilise the sustainability elements.	Educates the occupant on how to use the house's sustainability resources effectively.	Energy conservation is a function of a household's ability to implement the house manual.

		Curtailment initiatives	Household occupants practicing energy saving habits	Households will reduce their energy consumption.	Energy conservation is a function of household's proactive ability to reduce consumption.
	Market Strategies	Green/ sustainability-link bonds	Financial instrument that requires the borrower to meet sustainability metrics.	Mandates the borrower to implement energy saving indicatives into their building design.	Level of savings will depend on the bond's conditions.
Environmental	On-site renewable	Solar	System converts insolation into electricity.	Reduce the demand for fossil fuel energy.	0%-100% renewable energy supply depending on size of system.
		Wind	System that converts wind into electricity	Reduce the demand for fossil fuel energy.	0%-100% renewable energy supply depending on size of system.
		Use renewable resources to generate energy	Burning of renewable resources to generate power.	Reduce the demand for fossil fuel energy.	0%-100% renewable energy supply depending on size of system.
	Off-site renewable	Purchase renewable energy	Purchasing off-site renewable energy.	Reduce the demand for fossil fuel energy.	At least 50% of water heated by means other than electricity (Nedbank, 2020).
	Energy Storage	Electrical energy storage	Storing of electrical energy.	Renewable electricity is stored for when it is not being generated.	0%-100% renewable energy storage depending on size of the battery.
		Thermal energy storage	Storing of heat energy, generally in the form of hot water.	Excess renewable energy can be used to heat water for when it is not being produced.	0%-100% renewable generated hot water storage depending on the size of the cylinder.
Economic	Fixtures	LED lighting	Produces light up to 90% more efficiently than conventional lights.	Reduces the amount of energy required to provide artificial light.	54% energy savings on lighting (Zeb *et al.*, 2016).
	Appliances	Energy efficient appliances	Uses less energy to achieve the same performance as alternative appliances.	Reduces the amount of energy required to perform tasks by alternative appliances.	Level of savings will depend on the number and efficiency degree of appliances.
	Energy management	Smart electrical grid	Directs energy within an electrical grid to reduce electricity wastage.	Reduces energy consumption and wastage.	14% energy savings can be achieved (Arens *et al.*, 2005).
		Smart meters	Records energy use in real time.	Provides households with real time data to reduce energy consumption.	Energy conservation is a function of household's proactive ability to reduce consumption.
	Water heating	Thermal water heating	Water is heated using the sun.	Less electrical energy is required to heat water.	50% of hot water must be non-grid energy produced (Nedbank, 2020).

2.8 Carbon Emission Life Cycle Analysis

Carbon emissions are released throughout a building's existence, ranging from material manufacturer, construction, operation and demolition. In some building types, embodied emissions can exceed operational emissions even over the building's life cycle (Ibn-Mohammed *et al.*, 2013). This finding challenges the traditional focus of reducing operational energy use, highlighting the importance of considering the full life cycle impact of buildings.

The variations in these estimates can be attributed to several factors. First, the type of building being assessed plays a crucial role, as different building categories (e.g., residential, commercial, industrial) have distinct energy requirements and material compositions. Second, the intended use of the building significantly influences its emissions profile, with factors such as occupancy patterns, energy consumption behaviours, and maintenance practices affecting both embodied and operational emissions (Tejero *et al.*, 2018). Third, the selection of building materials and construction methods are a critical determinant of embodied emissions. Materials with high embodied energy, such as concrete and steel, contribute more significantly to a building's overall carbon footprint compared to materials with lower embodied energy, such as timber (Minunno *et al.*, 2021). Techniques such as prefabrication and modular construction potentially reduce embodied energy compared to traditional methods (Hannoudi *et al.*, 2024). Finally, geographic differences, including climate conditions, local building codes, and availability of sustainable materials, further contribute to the observed variations in embodied emissions (Lima *et al.*, 2021). For instance, buildings in regions with stringent energy efficiency regulations may exhibit different life cycle emission profiles compared to those in areas with less rigorous standards. Overall, these diverse factors underscore the complexity of accurately assessing and mitigating the carbon emissions of buildings, necessitating a comprehensive and context-specific approach to sustainable construction.

Utilising a life cycle carbon emission calculation will offer valuable metrics for analysing and comparing the environmental impact of buildings (Schwartz *et al.*, 2018). Within the built environment, EN15974 is an established standard used to measure the environmental impact of a building throughout its life cycle (Van Gulck *et al.*, 2022). RICS (2023) expanded this model to encompass the whole building's carbon life cycle iterating that the model is intended to evaluate a building from the production of materials through to the building's end of life. This methodology will allow a developer to determine if the reduced embodied carbon at construction will be less than the operational carbon. Consequently, preventing a developer from focusing on either operational or embodied carbon at the expense of the ignored carbon (RICS, 2023). Figure 2.7 below illustrates the RICS whole life carbon assessment framework and the proceeding passages will unpack the modules.

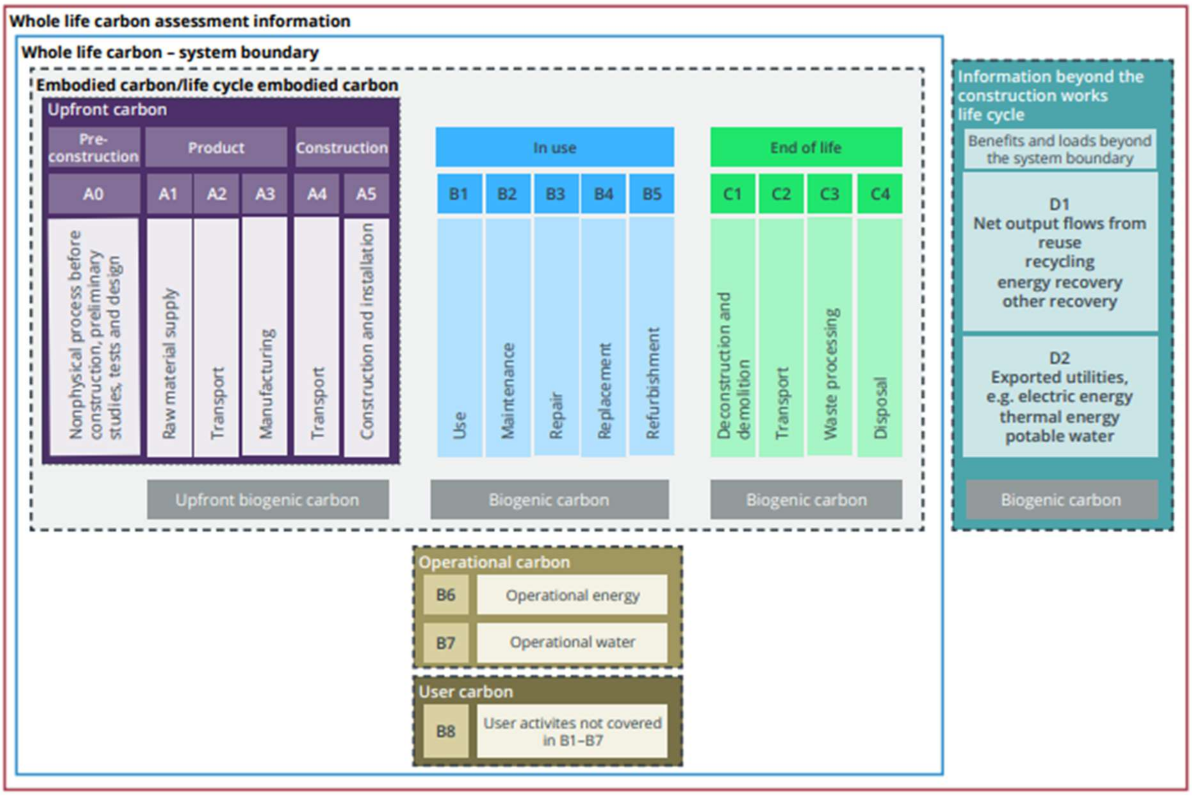


Figure 2.7: Whole carbon life cycle assessment framework (RICS, 2023)

Life cycle A (Purple – Upfront Carbon) encompasses all carbon emissions associated with the construction of a building, including works required to transport material to site before construction may take place:

- Module A0 (Pre-construction) addresses carbon emissions associated with construction preparation, such as land surveys.
- Module A1 – A3 (Product) covers carbon emissions attributed to material extraction, transportation and processing for the manufacture of building materials.
- Module A4 – A5 (Construction) encapsulates carbon emissions produced from transporting materials and machinery to construction sites and all emissions emitted to erect a structure.

Life cycle B (Blue – In Use) encapsulates all carbon emissions generated or added through repairs during a building's operational phase:

- Module B1 encompasses direct emissions and removals resulting from construction products, such as CO_2 absorption through the carbonation of concrete.
- Module B2 – B4 address material-related emissions arising from the repair and replacement of any building elements.
- Module B5 focuses on any refurbishment, retrofit or building extension.
- Module B6 (Brown – Operational Carbon) accounts for the energy consumption of the building.
- Module B7 (Brown – Operational Carbon) covers water use of the building.
- Module B8 encompasses occupant activities not included in the other models and could include, emissions from vehicles for example.

Life cycle C (Bright Green – End of Life) encapsulates carbon emissions incurred through the demolition of a building:

- Module C1 – C4 address impacts at the end-of-life stage of a building, encompassing activities like demolition or deconstruction, waste processing, recovery or disposal, and the associated transportation carbon emissions.

Life cycle D (Turquoise - Information beyond the construction works life cycle):

- Module D1 address the carbon emissions off-set from the re-use, recycling, energy recovery or materials sent to landfill from all modules, except for stages B6 – B8.
- Module D2 encompasses utility exports arising from the operational phase of a building, modules B6 – B8.

The complexities of buildings make them challenging to simulate a life cycle assessment (LCA). The largest LCA variations often occur during the design phase where material and design variability and uncertainty are prevalent (Marsh *et al.*, 2023). Consequently, addressing and effectively communicating uncertainty at this stage becomes even more crucial. Obstacles, such as limited access to environmental product declarations and the absence of a standardised procedures, further complicate this challenge (Marsh *et al.*, 2023).

2.9 Adopted Theoretical Framework

This section will revise the theories that will underpin the research and describe the process used to develop the assessment framework.

2.9.1 Theory of Change

Andrews and Reinholz (2020) argued that theory of change is project focused and evaluates the project's outcome, which is informed by change theory. According to Fullan (2007), change theory provides the knowledge needed to develop strategies that achieve results. Coryn *et al.* (2011) alluded to the theory underpinning the approach required to understand how a task can be broken down and how it works. This theoretical framework will provide the foundation which explains the links between activities, resources, outcomes or impacts (Connell and Kubisch, 1998). Creating a theory of change begins with understanding and recognising the context where these links and activities will occur (Andrews and Reinholz, 2020).

Affordable housing does not always work in practice because households spend more money on utilities when they transition from the informal housing sector to the formal property sector (Barnes *et al.*, 2011; Isalou *et al.*, 2014). Therefore, the success of affordable housing is dependent on affordability in terms of the economic viability of operational housing costs. As discussed earlier, sustainability initiatives can reduce utility costs, transport costs, improve working opportunities and community living (MacKillop, 2013; Isalou *et al.*, 2014; Awasthi *et al.*, 2021; Salehi, 2022). Therefore, ANZEHs is the integration of energy sustainability into affordable housing, creating homes in well located areas that lower-income households can afford.

Based on the above, Figure 2.8 illustrates the framework that will underpin the investigation of the impact of ANZEHs in South Africa. As discussed earlier, sustainability is broken down into three pillars (Giddings *et al.*, 2002). The economic pillar focuses on reducing the cost of utilities and construction capital costs to improve the financial viability of an affordable house at inception and during the operational phase (Langston and Langston, 2008; Isalou *et al.*, 2014). The reduction in operational costs will go hand in hand with the environmental pillar, which seeks to reduce electricity consumption and produce clean energy (Awasthi *et al.*, 2021; Salehi, 2022). Whilst, a reduction in embodied carbon can result from consuming fewer materials or using alternative natural resources during construction (Robati *et al.*, 2021). While the social pillar seeks to improve a household's and developer's carbon emission awareness and drive demand for ANZEH (Arman *et al.*, 2009; Pomponi and Moncaster, 2016). Therefore, these three pillars of sustainability will improve the lives of affordable households through the productive use of natural resources, which will contribute to social growth through economic and environmental awareness (Maliene and Mulliner, 2015).

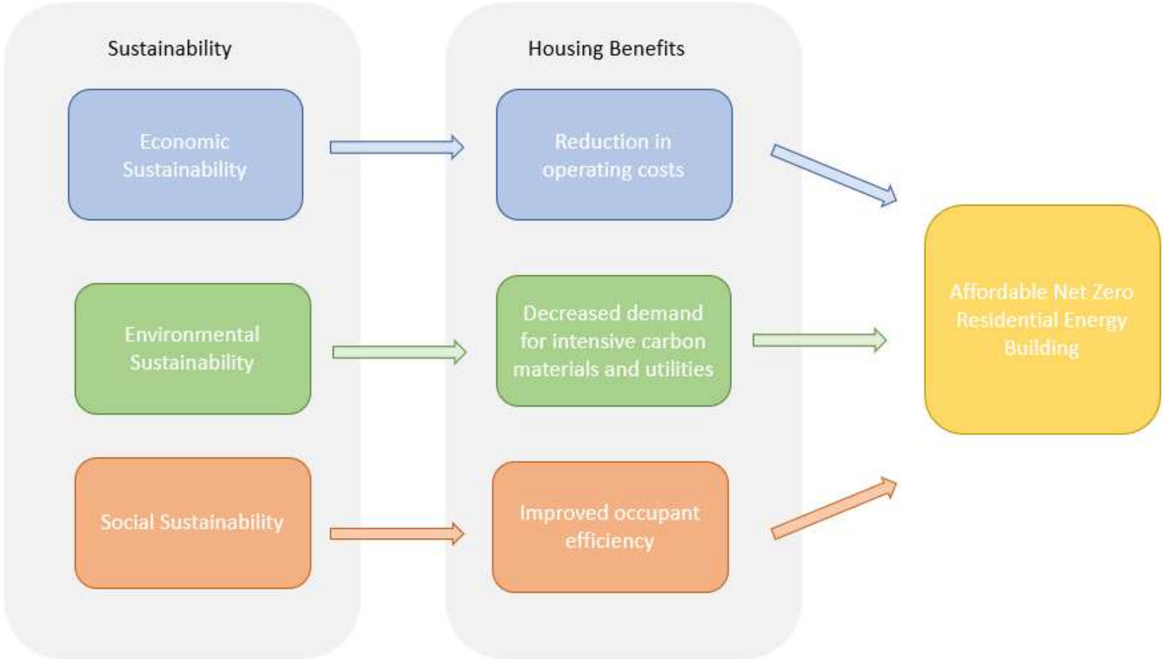


Figure 2.8: ANZEH sustainability framework

Certainly, the impact of ANZEH developments will have a positive effect on the embodied and operational carbon of affordable housing. This 3-pillar sustainability model provides a macro-overview of ANZEH for developers and policy makers to understand the impact of NZEB on affordable housing. While the framework design flow expressed in the conceptual framework will focus on the NZEB characteristics and elements that underpin an ANZEH.

2.9.2 Conceptual Framework

The ANZEH framework seeks to understand the difference between CAH and ANZEH and determine the NZEB characteristics that will allow developers and policy makers to transition from CAH to ANZEHs.

The ANZEH design framework is illustrated in Figure 2.9, which outlines the progression of key design principles and strategies. The figure begins by addressing the challenges faced by affordable housing, emphasising inefficiencies that lead to elevated energy consumption and increased environmental impact. Specifically, it highlights how poor building design results in high operational and embodied carbon. (Chastas *et al.*, 2018; Ahmadi *et al.*, 2020; Piao and Managi, 2023). The flow diagram then indicates the 5 main characteristics of NZEBs:

1. The production of renewable energy which offsets the household's energy grid demands (Sartori *et al.*, 2012).
2. The integration of energy efficient appliances and techniques (Deng *et al.*, 2014).
3. Improved building design will reduce upfront embodied carbon, and reduce the require energy to maintain a comfortable indoor environment (Chastas *et al.*, 2018).
4. The use of alternative building materials to reduce embodied carbon (Robati *et al.*, 2021).
5. Households can improve their energy awareness to actively consume less energy (Zhang *et al.*, 2010; International Energy Agency, 2018).

The amalgamation of these characteristics will promote energy conservation in a CAH and support the adoption of ANZEHs.

ANZEHs offer benefits such as reduced operational costs (Belussi *et al.*, 2019) through household energy optimisation and improved tenant energy habits (Never *et al.*, 2022), resulting in low operational carbon emissions (Belussi *et al.*, 2019; D'Agostino and Mazzarella, 2019). The integration of renewable materials and material re-use will promote low embodied carbon emissions (Robati *et al.*, 2021).

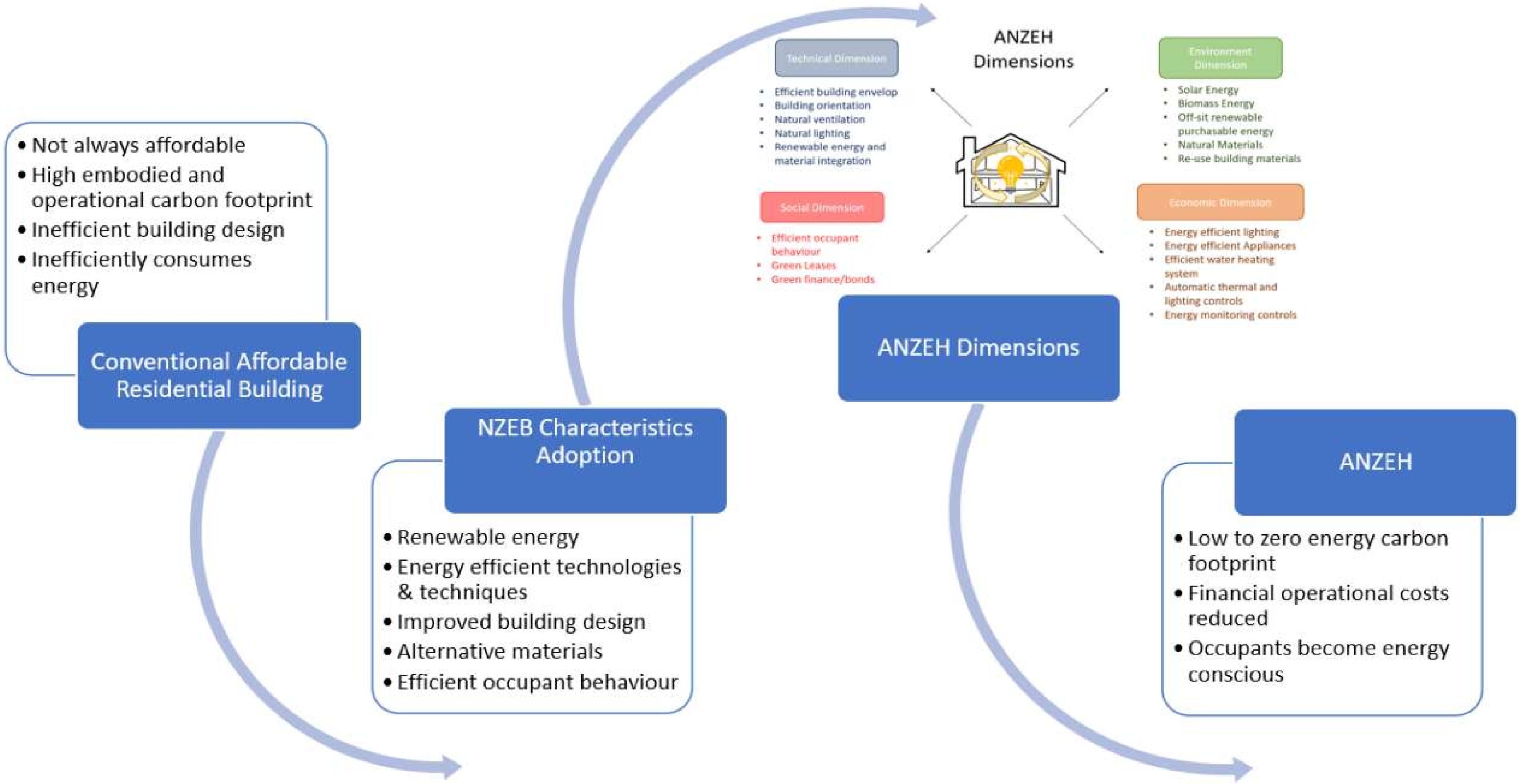


Figure 2.9: ANZEHs design framework flow

This research proposes that there are 4 critical ANZEH characteristics that will support the transition from CAH to ANZEHs. The study adopted a sustainability change theory approach to summarise the impact and elements of ANZEHs in a format that can be easily understood by developers and policy makers. While utilising a ANZEH design framework encompassing a technical, social, environmental, and economic dimension to examine the core elements.

2.10 Research Gap

Despite the extensive body of literature on affordable housing and sustainability in the built environment, a significant gap remains in the integration of these two domains within the South African context. While affordability has been examined through various economic lenses and housing supply mechanisms, the long-term operational costs are often overlooked. This omission is critical in South Africa, where rising electricity tariffs and unemployment, compounded by persistent energy insecurity have a direct impact on household affordability and well-being.

The literature also reveals a fragmented understanding of how sustainability can be embedded into affordable housing. Although NZEBs are gaining traction globally, their application in South Africa's affordable housing sector remains underexplored. Most NZEB research focuses on high-income or commercial developments, with limited attention given to how these principles can be adapted for low- to middle-income households. This is particularly concerning given South Africa's urgent need for housing solutions that are both economically viable and environmentally resilient.

Furthermore, there is a lack of a unified framework that combines affordability metrics with sustainability indicators. Current affordability assessments often fail to account for broader living costs such as transportation, access to services, and utility expenses which influence the true affordability of a home. Similarly, sustainability assessments tend to prioritise environmental performance without adequately considering the economic constraints of the lower population.

Policy and regulatory frameworks in South Africa have not kept pace with the evolving demands of sustainable affordable housing. Existing building codes, such as SANS 10400-XA, provide the minimum energy efficiency standards but do not adequately support the implementation of ANZEHs. There is a need for updated, enforceable policies that incentivise sustainable practices while ensuring affordability for end-users.

In summary, the research gap lies in the absence of an integrated, context-specific approach that addresses the technical, economic, environmental, and social dimensions of ANZEHs in South Africa. This study aims to by evaluating the impact of ANZEHs on the life cycle sustainability of affordable housing. It will do so by identifying critical success factors, assessing the role of materials, technologies, and construction techniques, and analysing the potential of ANZEHs to reduce life cycle emissions.

2.11 Summary of the Chapter

The literature review revealed that challenges around affordable housing are not only a South African challenge, but a global hurdle. The need for affordable housing to promote economic wellbeing within cities has become more pronounced, however high accommodation costs has resulted in the growth of informal settlements on city peripheries. Affordable housing seeks to overcome this financial hurdle by offering accommodation that does not exceed 30% of a household’s income, while being well located. South Africa’s large housing backlog, high construction costs, and increasing operating costs (i.e.: Rates and taxes, electricity, etc) has prevented the supply and uptake of cost-effective housing.

Affordable housing seeks to provide dignified housing to the lower-income class, however the literature has revealed that in practice affordable housing does not fulfil its goals. A sustainable approach to affordable housing must be taken, the built environment is striving to improve its sustainability by adopting materials and construction techniques to promote economic, social and environmentally sustainable living. However, South Africa’s building codes do not propagate sustainable construction practices as seen with SANS 10400-XA which indicates the minimum sustainability standards that must be met.

Subsequently, the above factors emphasise the need for sustainable affordable housing. Moreover, many countries around the world are encouraging net-zero energy housing to alleviate energy consumption. Energy is consumed throughout a building’s life cycle from construction to operation. A NZEB seeks to alleviate the generation of carbon emissions from construction, operation and demolition.

Considering that a household's accommodation expenses cannot exceed 30% of its gross income, and NZEBs will not emit carbon emissions. ANZEHs aim to blend these principles, crafting homes that consume net-zero energy while remaining economically viable. The cost-effectiveness of an ANZEH hinges on strategic design approaches and the efficient use of energy-saving technologies.

The following chapter presents the research philosophy and paradigm that guided the study's data collection and analysis.

3 RESEARCH METHODOLOGY

3.1 Introduction

This chapter presents the philosophy that serves as the foundation for the research, the chosen methodology, and the subsequent justification. Focus will then be paid to the interview process and the data analysis used. Finally, recognition of any matters pertaining to reliability, validity and limitations will be made.

3.2 Research Philosophy

The research philosophy underpins the entire research process, shaping how knowledge is developed, interpreted, and applied. As Greener (2011) explained, the researcher's comprehension of a study and the logical process to draw conclusions stems from the research's philosophy. In a study by Saunders *et al.* (2015), the research philosophy was described as a set of assumptions and beliefs about the development of knowledge. Put differently, the research philosophy serves as a framework for a researcher's thinking and guides the acquisition of new, reliable knowledge about the research subject. It forms the basis of the research process, including its design, execution, and analysis. For this research, which investigates the impact of ANZEHs on the life cycle sustainability of affordable housing in South Africa, a realist philosophy was adopted.

Philosophical bases play a crucial role in influencing our perception of the world, our beliefs, our understanding and approach to addressing research challenges. Coşkun (2020) noted that the paradigmatic roots will also influence the objectivist or constructivist approach. Objectivist-oriented researchers must find a middle ground between the naturalistic and positivist approaches, emphasising that researchers can hold personal values but should strive for objectivity (Coşkun, 2020). In essence, the social reality under investigation exists independently of us, meaning that social actors do not shape the existence of the social world (Saunders *et al.*, 2015). In contrast, constructivist researchers give precedence to logical procedures when developing theoretical explanations. They posit that reality emerges through social interactions, where social actors collaboratively establish partially shared meanings and interpretations (Saunders *et al.*, 2015; Coşkun, 2020).

However, a new modern approach has gained influence which combines these philosophies known as realism (Akpan, 2022). This approach combines the integration of values and interpretive meanings with a commitment to considering explanation as a legitimate objective in social research (Hall, 2013). Given the complex interdisciplinary realm of the built environment and overlapping domains like engineering, social sciences, and management. The study embraced this philosophical approach grounded in realism. This approach is particularly suited to this study due to its ability to bridge the gap between positivist and interpretivist paradigms. It acknowledges that while an objective reality exists, our understanding of it is shaped by social, contextual, and experiential factors (Hall, 2013; Akpan, 2022). This is essential in the built environment, where technical, economic, and social dimensions intersect. Realism allows the study to explore both measurable outcomes (e.g., energy savings, carbon emissions) and contextual influences (e.g., household behaviour, policy frameworks), aligning with the research aim.

There is significant ongoing debate among academics regarding the most appropriate research paradigm to adopt, which is rooted in a philosophical rather than a methodological approach (Krauss, 2005). The philosophical approach encompasses key aspects such as defining the problem statement, data collection, processing, and data analysis (Andriukaitene *et al.*, 2018). While a methodological approach serves as the research strategy that transforms philosophical principles into guidelines that dictate how research must be conducted (Tuli, 2010). The chosen research paradigm is explored in the proceeding section.

3.3 Research Paradigm

The built environment is a highly intricate field that encompasses a variety of professions dedicated to developing, operating and maintaining structures and infrastructure. This involves the amalgamation of places, people, technologies and processes, fostering a multi-disciplinary environment incorporating the domains of the engineering, social sciences, and various management facets, including financial, legal, political, human resources, and the natural sciences (Knight and Ruddock, 2009). Consequently, it is imperative for scholars to comprehend the paradigms that shape this field and align their work with the theories and practices from relevant disciplines (Walsh *et al.*, 2021). Abson *et al.* (2017) proposed that researchers must draw inspirations from system thinking and prioritise transformational interventions with a focus on key leverage points. This thought process will provide a researcher with a deeper understanding of their research's systemic relationships to enhance knowledge production and institute meaningful change. The realist paradigm supports the use of a mixed-methods approach, which combines qualitative and quantitative research methods. This approach was selected to provide a comprehensive understanding of ANZEHs by capturing both measurable outcomes (e.g., energy savings, carbon reductions) and contextual insights (e.g., implementation challenges, behavioural influences). The integration of these methods aligns with the interdisciplinary nature of the research. Subsequently, to gain a thorough understanding of how ANZEH influences the long-term sustainability of affordable housing in South Africa, it is imperative to explore the interplay between the social aspects of ANZEH, including the necessary knowledge for its implementation and its feasibility within the South African context, and the reductions in GHG emissions. The researcher chose to employ an exploratory mixed method grounded in the philosophical underpinnings of realism. It further enabled the research question to be addressed by incorporating both qualitative and quantitative methodologies, allowing for a more in-depth understanding of ANZEH while acknowledging the complexity and depth of the built environment.

Krauss (2005) noted that quantitative and qualitative researchers often work with distinct assumptions, which can result in varying outcomes and interpretations (Patton, 2014). Thus, it is essential for the chosen paradigm to align with the most appropriate methods and methodology for conducting a research investigation (Alharthi and Rehman, 2016). However, Crossan (2003) argued that the distinction between different research methods and the demarcation between quantitative and qualitative philosophies are often exaggerated, and it is common in contemporary research to employ triangulation of methods. The amalgamation of these methods has the potential to extract greater insight and breadth in a subject matter which could not be achieved if only a singular approach is adopted (Almalki, 2016). The subsequent sections will offer a more comprehensive exploration of each individual research approach and how they are amalgamated into a mixed method approach.

3.3.1 Qualitative Approach

Qualitative research, is grounded in a constructivist paradigm where the existence of an objective reality is challenged (Duschl and Lythcott, 1990). It focuses on words and observations to convey reality and strives to depict individuals in natural situations. This approach fosters data richness and holism by situating results within real-life contexts, thus effectively capturing the experiences of people's lived realities (Amaratunga *et al.*, 2002). The social world revolves around the individual, and reality is perceived differently by different individuals within a constructivist and interpretivist paradigm (Saunders *et al.*, 2015), supporting Duschl and Lythcott's (1990) observations.

This approach incorporates methods such as guided interviews and observations which are non-standardised to allow questions and procedures to alter during the data collection process in an interactive approach to pursue new emerging themes during the data collection process (Saunders *et al.*, 2015). Given this data collection approach, qualitative approaches aims to ascertain how an outcome is perceived, how to practicality implement it or how effectively it was adopted (Proctor *et al.*, 2011).

3.3.2 Quantitative Approach

Quantitative research emphasises the use of numerical and statistical data to investigate the research questions (Amaratunga *et al.*, 2002). This approach embodies a positivist perspective, wherein assumptions are subjected to empirical data and statistical analysis for testing (Saunders *et al.*, 2015). This framework stands as a methodological basis for researchers to uncover the causal mechanisms that underpin various phenomena in diverse fields, such as the built environment (Ponterotto, 2005). Kothari (2004) iterated that this method focusses on measuring data and it is generally associated with the positivist paradigm. This paradigm assumes that data is not manipulated when observed and aims to describe and measure observations (Krauss, 2005). Amaratunga *et al*. (2002) emphasised that quantitative approaches are advantageous for analysing the behavioural aspect of the built environment. These approaches offer comparison and replicable methodologies, promote the independence of the observer, and facilitate the measurement of descriptive elements within the built environment. Therefore, this method excels in measuring variables such as the cost or material quantity associated with a building's life cycle. However, physiological and personal motivating factors play a crucial role in research on the built environment, and this approach does not effectively facilitate the measurement of human behaviour or emotions (Amaratunga *et al.*, 2002).

3.3.3 Mixed Method Approach

The mixed-method approach was adopted to leverage the strengths of both qualitative and quantitative research. This integration allows for a more holistic understanding of the research problem.

The mixed method approach is a contemporary approach that combines elements of quantitative and qualitative research, often considered a middle ground (Krauss, 2005). The fundamental elements and theoretical characteristics elicited benefits through the amalgamation of positivism and interpretivism theoretical frameworks which could never be achieved using a single method (Dawadi *et al.*, 2021). This approach provides researchers with the ability to answer a research question extensively while generalising the findings across a population. Dawadi *et al.* (2021) further iterated that this approach unpacks the complexities of social phenomena's, aids in resolving conflicting outcomes that may arise from different research methods, and allows a researcher to answer explanatory and confirmatory research questions simultaneously. In essence, this approach will allow a researcher to develop an overall picture of the investigation by utilising unstructured interviews or observations, and use quantitative analysis to evaluate the descriptive or behavioural elements of the built environment (Amaratunga *et al.*, 2002).

3.4 Research Approach

Figure 3.1 illustrates the approach that this research adopted to investigate the impact of ANZEHs in South Africa. To assess the impact of ANZEH on the environmental life cycle sustainability of free-standing houses in South Africa, this study adopted a structured research approach. The research framework was shaped by the research aim, objectives and preliminary literature review. This was followed by a systematic literature review and the development of the theoretical framework that established the backdrop for the findings. Attention was then paid to the methodology approach and data collection which took a two-tiered approach. Semi-structured interviews were conducted with sustainable development and affordable housing experts, and content analysis was used to analyse the data. Secondly, the ANZEH models were generated based on the feedback from the interviews. The findings were used to validate the research conclusions and identify areas for further exploration. This research sought to contribute to the greater understanding of ANZEH, supporting reductions in embodied carbon housing design, decreasing energy consumption, raise energy conservation awareness, and encourage the adoption of ANZEH in South Africa.

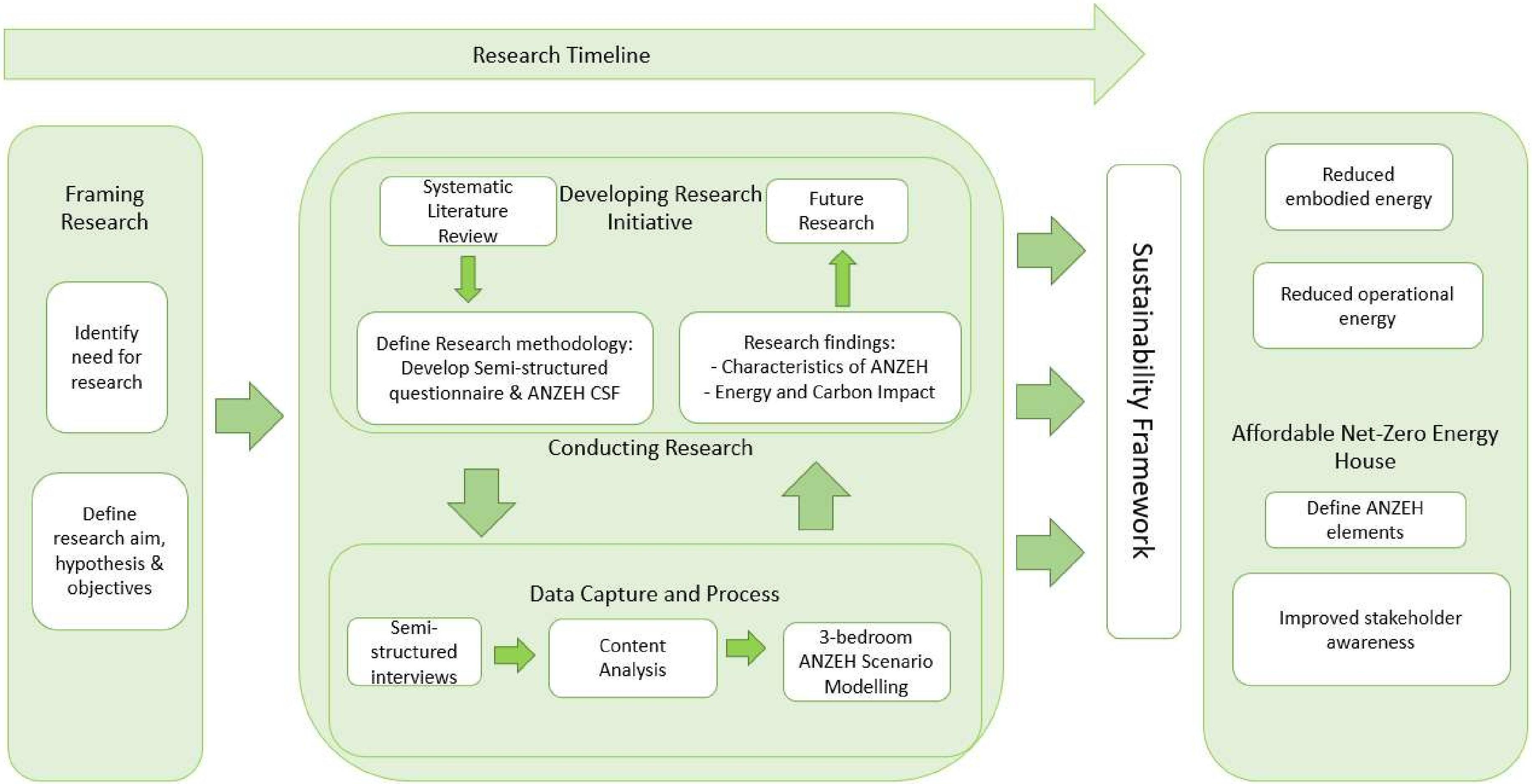


Figure 3.1: Research development timeline

3.5 Adopted Strategy and Research Approach

Kapoulas and Mitic (2012) contend that there is no singular correct paradigm or approach, and the choice of methodology depends on the research context. To comprehend the impact of ANZEH on the life cycle sustainability of affordable housing in South Africa, it is essential to investigate the relationship between the social constructs of ANZEH (specifically, the knowledge required to develop ANZEH and its practicality within South Africa) and the associated costs and reductions in GHG emissions. To achieve this, it is imperative to employ an appropriate research methodology. In selecting the most appropriate approach, the researcher considered several critical factors, including the primary research question, research objectives, the data collection methods and the type of analysis to answer the 'what' and 'how' questions outlined in Chapter 1, 1.5 Research Question.

Therefore, the methodology for this study employed an exploratory mixed method approach comprising of qualitative and quantitative approaches. The purpose of employing an exploratory sequential mixed methods design is to initially gather qualitative data (Tashakkori and Teddlie, 2003), facilitating the exploration of a ANZEH. Subsequently, this is followed by the collection of quantitative data to elucidate and provide explanations for the relationships identified in the qualitative data (Tashakkori and Teddlie, 2003). Figure 3.2 provides a graphical representation of the exploratory mixed method approach, where qualitative data was first collected before quantitative data was used to elucidate relationships within the qualitative data.

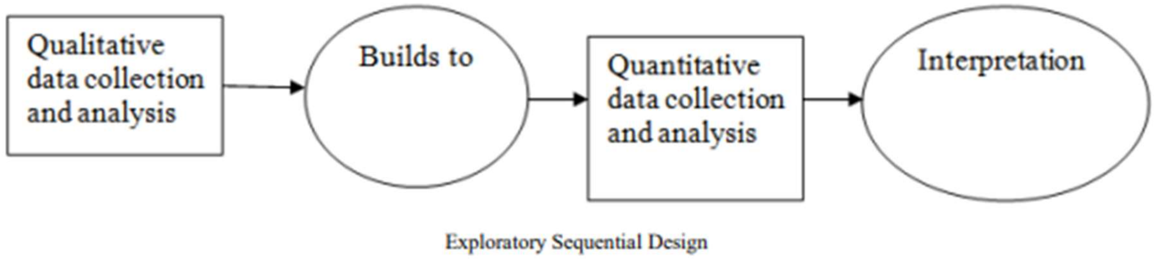


Figure 3.2: Exploratory mixed method approach (Subedi, 2016)

This data combination was selected to exploit the strengths of both methods while mitigating their weaknesses (Frels and Onwuegbuzie, 2013). Moreover, utilising both methods will yield greater insight and understanding of the built environment (Dainty, 2008). This method combination alludes to the research following a triangulation methodology, incorporating the constructivist approach (Questionnaires) and positivist approach (Building modelling) (Duschl and Lythcott, 1990; Crossan, 2003; Saunders *et al.*, 2015). Within this methodology framework, the mixed methods approach will derive alternative and deep insight into the workings of ANZEH within the complexities of South Africa's built environment (Dawadi *et al.*, 2021).

3.6 Method of Data Collection

The unit of analysis is not always the same as the unit of data collection, it represents what the researcher is examining (Yin, 2006). This distinction is crucial for drawing meaningful conclusions from the data and maintaining the research's integrity, as noted by Lavrakes and Roller (2015). The researcher took a phased approach conducting qualitative interviews and quantitative building modelling to answer the primary research question.

Qualitative data was procured through in-depth semi-structured interviews conducted with sustainability specialists and professionals. The primary objective was to gain insights into various aspects of affordable housing. These discussions delved into the professional perception about affordable housing, the practicability and extent of implementing ANZEH within the South African context, exploration of the energy and environmental implications tied to ANZEH implementation, analysis of building elements significantly contributing to embodied carbon, and an examination of housing activities that hold substantial contributions to CO_2 emissions.

Quantitative modelling was conducted through the utilisation of Revit to generate a three-bedroom house design. The design was formulated based on typical affordable house drawing acquired from an established affordable housing organisation in Cape Town. Following the creation of these models in Revit, they were fed into One Click LCA to estimate the life cycle GHG emissions associated with the house's design.

Consequently, the researcher analysed the sustainability life cycle impact of ANZEH in South Africa, by answering of the research question, analysing the interviewee feedback, ANZEH attributes, and modelling an expected ANZEH. This will allow the researcher to identify any relationships or trends between ANZEH and the sustainability life cycle impact, to refute or repudiate the research question.

3.6.1 Qualitative Data Collection

3.6.1.1 Adopted Semi-structured Interview Method

An interview is essentially a structured conversation interaction between a participant and a researcher, primarily focusing on questions related to the research study (deMarrais, 2003). Interviews can take various forms, but the two primary approaches are structured and unstructured (Saunders *et al.*, 2015). However, Doody and Noonan (2013) indicated that there is another method known as the semi-structured interview, which combines elements of both structured and unstructured interviews. Brinkmann (2014) supports this notion by indicating that there are similarities and distinctions between the interview methods.

Structured interviews involve a predetermined set of questions, with little room for deviation, ensuring that all interviewees are asked the same questions (Corbin and Anselm, 2015). While this method limits the interviewees' responses and depth of data collection beyond the predefined questions (Fellows and Liu, 2015), it simplifies data arrangement, manipulation, and analysis (Dumay and Qu, 2011).

On the contrary, unstructured interviews start with a single question, and the interviewee is given the freedom to narrate their story without significant intervention from the interviewer (Brinkmann, 2014). Chauhan (2022) observed that the prevailing literature predominantly perceives unstructured interviews as inferior. However, it's important to acknowledge that unstructured interviews provide a degree of freedom, as they impose minimal constraints on the formulation of questions and actively encourage follow-up questions. This flexibility fosters a deeper exploration of meanings compared to structured interviews (Chauhan, 2022).

Semi-structured interviews combine aspects of both structured and unstructured methods. Interviewees are presented with a standard set of questions but can provide additional information they consider relevant (Mannan and Afni, 2020). This method allows the interviewer to interact more freely with the interviewee, pursuing emerging themes during the conversation (Gray, 2014). It enhances the interviewer's understanding of the subject matter and improves the effectiveness in conveying and capturing the richness of the interviewee's responses (Mannan and Afni, 2020).

The researcher chose the semi-structured interview method due to its exploratory nature regarding perceptions and opinions (Mannan and Afni, 2020). Using open-ended questions which allowed interviewees to express their thoughts comfortably and expansively. Moreover, the flexibility in the interview structure permitted the interviewer to explore topics not explicitly included in their pre-determined questions, fostering an engaging interview environment that generated more comprehensive data.

3.6.1.2 Interview Design

Appendix A sets out the interview questions which were built according to the theoretical framework outlined in Chapter 2. The questions were created to understand the rationale and practicality of ANZEH in South Africa, the feasibility of developing an ANZEH, and the impact of ANZEH on GHG emissions. The interview questions were broken down into 4 sections, namely: 1) General questions; 2) Impact on economic sustainability; 3) Impact on environmental sustainability; and, 4) Impact on social sustainability. These sections allowed the researcher to gather information pertaining to the impact of ANZEH on the life cycle sustainability of affordable housing in South Africa.

Section 1 was created to establish an affordable housing baseline, understand the types of housing designs adopted, the processes used to develop a sustainable affordable house, and the practicality of delivering ANZEH within the context of South Africa.

Section 2 focused on the economics side to uncover the financial implications of ANZEH. These included factors relating to the most optimal cost to energy conservation techniques, the impact of energy efficiency techniques of life cycle costs and financial benefits enjoyed by the tenants.

The basis of section 3 was to understand the environmental impact of an ANZEH. This looked at the embodied and operational carbon footprint of the building, alternative energy supplies, and the main building elements that reduce GHG emissions.

Section 4 aimed to understand the social implications of ANZEH on tenants, barriers to entry, and the influence that different stakeholders have during the life cycle of an ANZEH.

3.6.1.3 Sampling Strategy

The sampling strategy for interviews was designed to select relevant industry professionals within the constraints of the limited availability of ANZEH experts in South Africa. A focus on key stakeholders directly involved in the design, construction, and assessment of green buildings and affordable housing developments were approached. This targeted strategy enabled the selection of four interviewees whose expertise aligned closely with the research aim and objectives. The small sample size reflects the nascent state of ANZEH initiatives in South Africa.

3.6.1.4 Data Saturation

Data saturation was achieved despite the small sample size of four interviewees, reflecting the limited scope of ANZEH expertise in South Africa. Given the niche nature of the research topic, a purposive sampling strategy ensured that participants were highly knowledgeable to facilitate a comprehensive exploration of relevant themes, including design strategies, material choices, and challenges surrounding sustainability strategies and development costs. Recurrent patterns and consistent themes emerged across interviews, indicating that additional participants would likely yield diminishing returns. The depth and specificity of perspectives and practical knowledge enriched the study with context-specific insights and experiences.

3.6.2 Quantitative Data Collection

3.6.2.1 Whole Life Cycle Building Emission Modelling

This section outlines the modelling tools, data sources, and site-specific assumptions used to model the whole life carbon emissions. The data collection process involved multiple tools and methods to quantify the whole life carbon emissions of an ANZEH. Carbon emissions were modelled using a combination of OneClick LCA and the Edge App because they were recommended through the interviews as an industry recognised method to calculate a residential building's expected carbon emissions.

The collected affordable housing design was first converted to a Revit model, as a medium for the OneClick LCA plug-in to capture the building elements in an accurate manner. Additionally, the building was modelled within Cape Town falling under climate zone 4 as per SANS 10400-XA (2011). More specifically, the Parklands suburb was selected as the site location within the Cape Town precinct because the average house price is R1.2m. Additionally, this suburb has affordable land, growing economic activity and it is expected that the city will expand past this peripheral within the next 3 – 5 years, making it a good real estate investment. Consequently, Parklands was selected as the site location for calculating transport distance assumptions, with building material sources considered within a 30km radius.

While the modelling in this study was conducted for a single location, it is important to recognise that South Africa encompasses a diverse range of climate zones. These zone variations influence building performance factors such as R-values, solar gain, and construction requirements, which in turn affect embodied and operational carbon emissions. By focusing on one climate zone, the study provides a focused geographical analysis, however, this approach limits the generalisability of the findings across other regions.

The OneClick LCA program was used to simulate the embodied carbon dioxide equivalent (CO_2e) for modules A1 – A5, C1 - C4 and D1. The program is user friendly with a comprehensive database consisting of environmental product declarations that undergo a verification process to guarantee consistency and accurate assessments. However, it is noteworthy that the system lacks comprehensive South African data points, and comparable materials from diverse manufacturers are not widely accessible. This observation aligns with the feedback received from participant 1, who highlighted this as the program's drawback. Energy-efficient variables, such as reflective solar index and R-values, were sourced from manufacturer specifications, while the RICS Whole Life Carbon Assessment Guide (2023) was used to estimate wastage and repair values when these were absent from environmental product declarations. Maintenance-related emissions (Module B2) were guided by the United Nations' (2023) global average of 40kgCO_2e/m^2 for South Africa.

Furthermore, it was noted that the OneClick LCA program features a rudimentary operational energy calculation. This involves the user inputting a singular energy consumption value, which is generalised over the entire lifespan of a building. However, this approach does not consider potential operating energy savings that could arise from utilising different building materials, techniques or appliances, re-enforcing the use of the Edge App for operational energy modelling. The operational energy (Module B6) was simulated using the Edge software to facilitate the energy consumption modelling of different ANZEH levels. The program serves to ascertain critical parameters such as liveable area, room type and size (e.g., bathroom, bedroom, and kitchen), and adjust consumption levels based on location, household size and building type. The software adjusts utility consumption levels based on building elements, materials and technologies. Given the research's scope, only carbon emissions stemming from electricity consumption were determined. This was achieved by utilising an emission factor of 1.013 kgCO_2e/kWh to convert kilowatt-hours to carbon emissions (Department of Forestry Fisheries and the Environment, 2024).

All carbon emissions data was captured in Excel for ease of analysis and presentation in Chapter 4.

3.6.2.2 Whole Life Cycle Cost Modelling

The whole life cycle cost was calculated by engaging with industry professionals to ascertain construction and demolition rates. A bill of quantities was retrieved from a developer and used to estimate the Base Case costs. Alternative material costs, such as those for cross-laminated timber and PV panels, were obtained from suppliers. Maintenance costs were derived using the Chartered Institution of Building Services Engineers TM65 manual. This choice was made as the researcher lacked access to repair schedules and the RICS guide (2023) deemed it a suitable alternative. This led the cost of repair to be a 10% function of the total construction costs. Energy consumption costs were calculated by multiplying the home's lifetime energy consumption by the current electricity rate (R2.6833 per kWh), extracted from a City of Cape Town municipal account. Demolition costs were calculated using rates obtained from an industry expert, and the cost of recycled materials was offset by multiplying the recycling ratio of the material by its cost.

3.7 Method of Data Analysis

The methods and techniques used to analyse the collected data are described below. Additionally, the presented data analysis techniques were applied to address the research question.

3.7.1 Qualitative Data Analysis

3.7.1.1 Interview Feedback Analysis

Qualitative data equips a researcher with the essential information for crafting a narrative or formulating a theory on a specific topic (Yin, 2015). However, Yin (2018) cautioned that non-statistical analysis can pose challenges due to variations in how individuals interpret the data. He also emphasised that the key to a successful analysis lies in discerning what to look for and developing a comprehensive understanding of your analytical approach. Furthermore, qualitative data is often more intricate than many researchers realise, and there are multiple methods for its analysis (Holloway and Todres, 2003).

This study will adopt the content analysis, which constitutes a systematic method for identifying, closely examining, and subsequently reporting the central patterns or themes that emerge from qualitative data (Yin, 2015). Content analysis serves as a robust qualitative research approach, enabling researchers to uncover and understand the deeper meaning and significance within their data. It involves a structured process of coding and categorising information to distil the essential insights, thus shedding light on the descriptive elements and narratives that underpin the data set (Castleberry and Nolen, 2018; Williams and Moser, 2019). Amanda and Ashley (2018) further emphasised the importance of researchers explicitly articulating their thematic process within their data procedures to enhance the overall value of their findings.

Therefore, the researcher employed a three-tiered coding approach (Williams and Moser, 2019). The initial stage involves open coding to identify broad and distinct concepts and themes. The second level of coding, known as axial coding, focuses on recognising the content themes, refining them, and categorising them with greater precision. Finally, selective coding will be employed to carefully select and integrate organised data categories from the axial coding stage, allowing for the emergence of a cohesive and meaningful narrative from the data (Williams and Moser, 2019).

NVivo software was used to facilitate the data analysis process, allowing for organisation, coding, and categorisation of interviewee responses. A tree node structure was built within NVivo to represent various codes. This hierarchical node structure allowed for the systematic buildup of selective codes, ensuring that data could be categorised at different levels of specificality while maintaining context. By iterating the data in this manner, the analysis revealed recurring patterns and provided deeper insights into the complexities of implementing ANZEH in South Africa. This coding approach is expressed under Appendix B and Appendix C.

3.7.2 Quantitative Data Analysis

3.7.2.1 Whole Life Cycle Building Emission Modelling

Building from the modelling process describe in section 3.6.2.1, this section presents the specific carbon emission modules assessed, the assumptions applied, and the calculation methods used to quantify the carbon emissions. The modelling process sought to quantify the estimated whole life carbon emissions generated by an ANZEH at three different levels, encompassing building elements and techniques that are typically associated with affordable housing projects. The modelling framework adhered to RICS whole life carbon assessment but, excluded Module A0 as it is considered negligible unless constructing a civil structure (RICS, 2023). Moreover, Module B7 and B8 will not be examined within the scope of this thesis. Further, Module

D2 utility exports were assumed to be zero for the purposes of this research. Therefore, modules A1 – A5, B1-B5, B6, C1 – C4, and D1 were evaluated.

Modules B1 - B5 were calculated in accordance with the RICS Whole life carbon assessment for the built environment guide. Carbon emission absorption by concrete was not accounted for in this study, resulting in the emissions for Module B1 being recorded as null. The guide advocates for the use of life cycle cost reports, operational or maintenance manuals to guide maintenance related carbon emissions (Module B2). If these reports are not available, module B2 impacts can be quantified using a total figure of 10kgCO_2e/m^2 gross internal area to encompass all building element categories if the building is in the UK, or 1% of modules A1–A5, whichever amount is higher. It is noted that assessments conducted in other countries may adopt this default figure, but if a national equivalent is available, it should be utilised instead. Given that the UK is a first world country, the 10kgCO_2e/m^2 is low in comparison to South Africa and the global average is 40kgCO_2e/m^2 as reported by the United Nations environmental programme (2023). Therefore, the 40kgCO_2e/m^2 will be used to extrapolate the maintenance carbon emissions because it is greater than the 1% emissions of A1- A5. Furthermore, each scenario has the same gross internal area, resulting in the same maintenance emissions. The emissions for Repair (Module B3) were computed following the methodology outlined in the Chartered Institution of Building Services Engineers TM65 manual. This choice was made as the researcher lacked access to repair schedules and the RICS guide (2023) deemed a suitable alternative. This led Module B3 to be calculated as the equivalent to 25% of Module B2 and 10% of Module A1-A3 impacts for mechanical, plumbing, and electrician components. Material replacement and refurbishment (Module B4-B5) emissions were calculated using the expected service life of materials specified in the RICS Whole life carbon assessment for the built environment guide.

Using the Edge App, operational energy (Module B6) was analysed to evaluate energy consumption levels for the ANZEH base case, scenario 1, scenario 2, and scenario 3. The analysis incorporated critical parameters, including liveable area, room type and size (e.g., bathroom, bedroom, and kitchen). Utility consumption levels were further refined by considering building elements, materials, and technologies. Within the scope of this research, the analysis focused exclusively on carbon emissions derived from electricity consumption, converted using an emission factor of 1.013

$kgCO_2e/kWh$ to determine CO_2 emissions (Department of Forestry, Fisheries, and the Environment, 2024).

3.7.2.2 Whole Life Cycle Cost Modelling

The analysis of the whole life cycle cost incorporated construction, operational, and demolition rates, which were informed by industry standards, a bill of quantities, and expert consultation. Building material costs were extracted from the bill of quantities, however, these costs primarily reflect material values and do not comprehensively account for labour, contractor preliminaries, or professional fees. To account for this, a 15% preliminary rate was applied to the rate build-up.

Repair costs were estimated as 10% of the total construction costs, while replacement costs were calculated based on the expected useful life of each material, multiplied by the number of anticipated replacements over a 50-year building lifespan. Operational energy costs were estimated by multiplying the lifetime energy usage (from EDGE App simulations) by the prevailing electricity tariff (R2.6833 per kWh). It is acknowledged that future changes in electricity prices were not accounted for in this analysis, and a constant tariff was assumed. Demolition costs were informed by rates provided by an industry expert, and the value of recycled materials was deducted based on the product of the recycling ratio and material cost. While these estimates provide a reasonable comparative basis for scenario evaluation, the results are subject to limitations due to the exclusion of inflation-adjusted labour costs, life cycle escalation factors, and discounted future cash flows.

3.8 Validity & Reliability of the Data

Saunders (2015) emphasised that reliability and validity play pivotal roles in assessing research quality, especially in the natural sciences and quantitative research within the social sciences. Validity pertains to the precision of measurements and the appropriateness of data collection tools, and reliability entails the consistency of measurements and tools used (Heale and Twycross, 2015). Maslak and Sürücü (2020) iterated that if a researcher focuses on the reliability and validity throughout their research, their research quality will be enhanced leading to more meaningful results.

Yin (2018) argues that researchers should meticulously acknowledge both the strengths and limitations of their research, as there exist various approaches to exploring a subject. Aspects of one research design may complement or shed light on the limitations and strengths of other research methods (Yin, 2018). Murnan and Price (2004) further emphasise that disclosing possible limitations is pivotal in revealing any potential systematic biases, whether known or unknown to the researcher.

In the context of this study, the researcher sought to investigate the impact of ANZEH on the life cycle sustainability of affordable housing in South Africa. A qualitative approach was the primary data collection method which inherently introduced subjectivity into the research process. Both the interviewees and the researcher may have been influenced by cognitive biases stemming from their individual worldviews. As a result, the research findings inherently reflect the perspectives and understandings of the participants, but also the researcher's interpretations. To ensure the reliability and credibility of the data, the interviewees were selected based on their expertise in the built environment. This selection process sought to capture informed and authoritative insights from experts who are actively engaged in the built environment, thereby enhancing the richness and applicability of interviewee feedback. Additionally, the researcher took deliberate steps to craft clear and specific questions, ensuring that the collected data was relevant and directly addressed the research questions.

On the other hand, quantitative analysis took the form of building modelling due to the limited adoption of ANZEHs in South Africa. The use of building modelling provided a framework to explore scenarios that would otherwise be impractical or impossible to examine in South Africa. To ensure the reliability and validity of the quantitative data, the building modelling drew direction from the interviews and RICS standards. This approach minimised the risk of errors arising from discrepancies between the model and real-world conditions, as highlighted by Law (2022) who noted that simulations serve as substitutes for experimenting with real-word systems. By adhering to these parameters, the building modelling achieved results that reflected the potential performance of ANZEHs, enhancing the credibility and applicability of the findings.

However, while a formal validation of the models was not conducted, the efforts stated above sought to ensure the credibility of the results. The research employed reputable and widely used tools, One Click LCA and the EDGE App, which are aligned with international sustainability standards. Inputs were carefully selected based on literature, interviews, and realistic building configurations. Nonetheless, the lack of external validation represents a limitation, and future work will benefit from formal calibration or real-world case study comparisons.

3.9 Ethical Considerations

Ethics in research forms the foundation for conducting high-quality research, which entails the standards and values that differentiate between acceptable and unacceptable behaviour, as outlined by Shah (2011). Various disciplines, institutions, and professions maintain specific codes of conduct aligned with their unique objectives. These standards not only facilitate the coordination of actions and activities within the respective discipline but also foster trust (David, 2015).

Several authors have expressed their viewpoints on essential ethical principles that researchers should uphold. These principles encompass: 1) securing participant consent to protect their anonymity; 2) ensuring researchers refrain from exposing participants to potential harm; and, 3) preserving participants' privacy while upholding a rigorous standard of anonymity (Donnelly and Trochim, 2001; Fouka and Mantzorou, 2011; Resnik, 2011; David, 2015). David (2015) emphasised the significance of adhering to ethical norms for several reasons. First, ethical norms serve to advance the research's fundamental goal, which is the pursuit of knowledge while ensuring that there is no misrepresentation. Second, ethics play a pivotal role in promoting the values crucial for collaborative work, given that research often involves cooperation and coordination among various stakeholders. Third, adherence to ethical norms enhances accountability. Fourth, it bolsters trust in the quality and integrity of research. Fifth, ethical norms contribute to the promotion of social values and morals.

Given the strategic importance of ethics in research, the researcher applied and obtained approval from the Faculty of Engineering and the Built Environment Ethics in Research Committee (EiRC). A copy of the ethics approval can be found under Appendix D.

The interview process was preceded by a consent form, refer to Appendix E, which outlined the study's objectives, clarified the rights and responsibilities of the participants, and indicated that participant information will remain confidential and anonymous throughout the research. Participants were actively requested to provide their voluntary consent to take part in the study, and it was explicitly communicated that they retained the option to discontinue their involvement in the research at any point. Consequently, it can be reasonably inferred that the study obtained the consent of its participants.

3.10 Summary of the Chapter

This chapter laid the foundation for the research design by explaining the methodological approach, data collection and analysis strategies. The mixed-methods approach was employed, involving the collection of both quantitative and qualitative data. Quantitative data was gathered through a BOQ, Revit was used to model ANZEH and One Click LCA was used to estimate the GHG life cycle analysis, while semi-structured interview questions were utilised for the qualitative phase. The primary data collection instruments included the qualitative interview survey, and a snowballing interview approach, while data analysis involved Revit and One Click LCA modelling, and thematic analysis to generate key emerging themes. The subsequent chapter will discuss the qualitative findings and unpack the quantitative analysis.

4 DATA ANALYSIS AND RESULTS

4.1 Introduction

In this chapter, the analysed data from qualitative and quantitative segments is presented. The qualitative section presents the selective codes developed from the content analysis, such as sustainability, the influence of ANZEH, and their practicality. These selective codes were identified and defined based on the study's objectives and ANZEH dimensions underpinned in Chapter 2, ensuring they align with the research goals. The purpose of the qualitative analysis was to 1) determine the critical success factors that underpin an ANZEH from a professional's viewpoint, and 2) identify the construction, material, technology, and building techniques that must be considered when developing an ANZEH. Following the exploration of the qualitative data, the analysis will transition into the quantitative modelling of the LCCE of an ANZEH at three varying degrees of sustainability. This structured approach ensures a comprehensive examination of the data, leading to a deeper understanding of the factors influencing ANZEH development and implementation.

4.2 Participant Backgrounds

To provide context for the insights gathered, the backgrounds of the participants involved in this study are summarised in Table 4.1. This table outlines the roles, education, and experience of the interviewees, all of whom have considerable expertise in the built environment. Their diverse backgrounds provide valuable perspectives on the development and operationalisation of ANZEH.

Table 4.1: Participant Backgrounds

Participants	Role	Education	Experience	Experience
Participant 1	Founder and director of a sustainability consulting firm.	B.Sc Electrical Mechanical Engineering	14 years	Specialises in sustainability and green building consulting for the built environment.
Participant 2	Head of property development for a nonprofit organisation.	B.Sc (QS) and an M.Sc (Construction Economics and Management)	30 years	Specialises in affordable and social housing development within South Africa.
Participant 3	Sustainable built environment consultant.	B. Tech Mechanical Engineering	17 years	Specialises in green buildings and energy efficiencies.
Participant 4	Environmental sustainability director.	B.Sc (Honours) Electrical Engineering	26 years	Supported the development of GBCSA green rating tools.

4.3 Qualitative Analysis

This section examines the selective codes derived from the NVivo content analysis. The process began with six initial content codes identified from the interviews, which were expanded into 10 axial codes and 11 selective codes (Williams and Moser, 2019). These codes were then refined and organised into a coherent structure to align the findings with the research topic and improve readability.

The analysis is presented as follows: first, the professional perspective on affordable housing in South Africa is explored to provide insights into its implementation. Next, the concept of ANZEH is analysed from an emissions perspective and a breakdown of the embodied and operational carbon emission principles. This is followed by an evaluation of the dimensions of ANZEH, identifying the drivers and initiatives necessary for its development. Lastly, the building elements and their associated technical specifications contributing to ANZEH are summarized.

4.3.1 Professional Viewpoint of Affordable Housing In South Africa

4.3.1.1 Participant Understanding

None of the participants provided a concrete definition of affordable housing, their consensus revolved around the understanding that it caters to a market segment facing financial constraints and who do not meet the criteria for RDP or social housing. Some participants did express their knowledge that affordability within the South

African context evolves around income brackets, but none of the participants could name the specific thresholds (These thresholds were discussed under section "2.2.2. What is Affordable Housing?"):

> Participant 1: "*I I'm aware of formal thresholds. Umm, I don't have them the front of mind, but in essence it's it's housing that caters to a part of our market that's has limitations on the affordability and I can't remember exactly what the threshold is. Hopefully we'll just refresh my memory now, but really the the the point is twofold. The one is the the affordability in in purchasing or renting thereof, and certainly also but less, I think of a focus area is the total cost of ownership or occupancy rather which includes utilities and the like which is I guess a part that I'm particularly interested in that is marrying those two that we don't just throw expensive technology on it which can make the energy consumption, water consumption lower but would drive up the purchase price or the rental rates.*"

These affordable discussions encompassed various considerations such as whether a household should acquire, or rent, based on their level of disposable income. Notably, the conversations extended beyond mere upfront costs, emphasising the comprehensive spectrum of expenses linked to ownership or renting. Participants highlighted concerns regarding the overall cost of ownership, acknowledging that affordability encompasses not only the initial investment, but also factors such as ongoing utility expenses and maintenance costs:

> Participant 2: "*…you should provide the best quality you can. You know, for these sorts of markets and you also have to try and make the design as robust as possible so that there's not a high maintenance cost or it won't remain affordable.*"

These broader considerations were expressed as pivotal concerns when deliberating the affordability of housing projects. The various interpretations of affordable housing revealed in the interviews align with the literature outlined in section 2.2.2. They reflect the diverse range of definitions, all converging on the notion that affordable housing should be aimed at financially constrained families.

4.3.1.2 Design Considerations

Participant 2 expressed the distinctive financial nature and simplified construction characteristics of affordable housing compared to other housing types to reduce costs. The participant emphasised the importance of efficiency within several facets, particularly in the allocation of floor space and room sizes, which consider family needs, and the comfortable accommodation of multiple occupants within a limited space. Every square meter of an affordable property is crucial, necessitating purposeful design without extraneous elements like corridors or passages which require costly fire standards. Therefore, the primary focus must remain on optimising the usable and habitable space in a cost-effective manner to reduce the capital costs.

At the same time, in standard affordable housing developments, principles such as property orientation for optimal thermal energy efficiency and utility usage, are integral considerations due to the residents' limited incomes. The specification of finishes needs to align with the affordable housing standard, maintaining a balance between cost and quality. Additionally, designs must be robust to minimise maintenance costs for both homeowners and/or landlords in the long run.

At the same time the design team and professionals with strong rapport and familiarity with each other's working styles must be selected as part of the development team. The rationale behind this approach is to avoid the communication and trust-building challenges that arise when teams frequently change. Participant 2 expressed that by maintaining team continuity, they bypass the need to continually establish teamwork dynamics and work habits, thus preventing the reinvention of the collaborative processes with every project. This approach fosters an environment where sharing ideas and promoting innovative initiatives becomes more comfortable due to the established camaraderie. Despite this, there's acknowledgment of the need to infuse new perspectives periodically to prevent stagnation within the team. Additionally, in the process of developing housing projects, market research plays a crucial role. While direct community engagement may not always occur, prioritising well-located areas with access to transportation, schools, and employment opportunities is integral to crafting a compelling and inclusive product for the affordable housing market.

4.3.1.3 Household Perception Towards Affordable Housing

Participant 1 and 2 alluded to housing perception as a critical consideration when designing a standard house or an ANZEH. In discussing housing preferences, there's a notable inclination towards a preference for single free-standing houses over units in complexes, reflecting a desire for ownership of a piece of land with a standalone dwelling rather than a sectional title. People favour physical ownership within South Africa, leaning away from rental arrangements and towards the possession of property.

Participant 1 highlighted that perception goes beyond ownership and low-income individuals tend to prefer traditional materials such as brick and mortar, steering away from sustainability. This preference for conventional materials reflects social challenges regarding the acceptance of experimental or alternative housing materials. Echoing this sentiment, Participant 2 shared their firsthand experience, noting a market preference for specific construction materials such as face brick over plastered walls. Notably, these preferences vary based on location. These insights underscore that housing decisions are heavily influenced by individual preferences and location-specific factors beyond merely financial considerations.

4.3.1.4 Measuring Sustainable Housing

Participants 1, 3 & 4 all indicated that a building's sustainability is graded using one of the following rating systems, GBCSA Green Star, Edge, or LEED. The rating systems mentioned by the participants mimic the primary green rating tools observed in the literature (Chapter 2.5.1), except for BREEM. Participant 1 expressed the prominence of Green Star and Edge, with LEED being less common in South Africa. LEED is not a popular tool because it is rooted in Western developed countries like the United States, which limits its adaptability to South Africa's environment and economic condition. Comparatively, the GBCSA Green Star is regarded as a more comprehensive and tailored tool for the South African context, covering a broader spectrum of factors including ecology, transportation, indoor environmental quality, and social aspects. This detailed approach in Green Star, is seen as more intricate and demanding, leading to higher consulting fees and a more challenging certification process. The interviewees shared similar sentiments, by indicating that the higher fees and the comprehensive nature of the tool has made the Edge rating tool more prominent.

Edge is noted for its simplicity with three components compared to Green Star's comprehensive approach, which involves about 15 elements related to green building practices. The choice between these tools might depend on various factors such as the developer's profile, available funding for consultants, and the project's specific needs. If the focus is on a comprehensive green building approach, Green Star might be preferable, whereas Edge could suit those aiming for a simpler, targeted strategy addressing energy, water, and embodied carbon. The decision-making process would likely involve considerations of the market, investors, or stakeholders involved.

It was noted that sustainability projects often proceed without pursuing formal certification, focusing instead on implementing sustainable practices without seeking formal recognition. This tendency largely stems from the considerable expenses linked with obtaining certifications with one participant indicating that they had built an Edge-ready development. The project met the Edge requirements but opted not to pursue formal certification due to the cost. The emphasis on Edge efficiencies was deliberate, particularly because the development targeted the affordable housing sector. Prioritising efficiency in electricity and water usage was crucial to ensure the operational affordability for households renting.

Participant 4's insights highlight the growing interest in sustainable developments, particularly in achieving net-zero energy. While initially embraced by a limited group of leading GBCSA Green Star Accredited Professions, interest in net-zero energy developments has spread among significant commercial property players. Although not widespread, this trend denotes a move towards net-zero practices, albeit mainly within the leading cohort. Additionally, participant 4 highlighted that Green Rating tools evaluate a building at the holistic level, and if a building does not have something that can be measured by the tool, then it is not seen as "green". This perception has started a shift in terminology towards calling it a "resource efficiency tool" instead of a "green rating tool" acknowledging its limitations if a facet is left out. This observation gains significance when assessing ANZEH, as ANZEH solely concentrates on energy conservation, leaving out other vital sustainability aspects. This limitation prevents ANZEH from achieving a green building rating within the GBCSA rating tools. Participant 1 expressed that the GBCSA has developed net-zero tools, namely: 1) Net Zero: Carbon; 2) Net Zero: Water; 3) Net Zero: Waste; and 4) Net Zero: Ecology which seek to resolve the above concerns.

4.3.2 Affordable Net-Zero Energy Housing

As indicated in the previous section, net-zero developments are beginning to gain traction within South Africa. However, these developments are only developed within a premium and niche market. Participant 1 indicated that net-zero energy developments has notably increased in the past two years. Initially, this interest was concentrated among a small group, particularly leading green star accredited professionals who were engaged in finding interested clients or initiating projects. However, interest is now spreading among the large commercial property players, who are experimenting with net-zero energy goals in several projects, signifying a shift toward mainstream adoption.

It was also noted that the widely used general term "net zero" is misleading as it does not specify what aspect of the building achieves net-zero status, such as embodied carbon, water, or electricity. Therefore, organisations and the media must start indicating the type of net-zero that a building has achieved to prevent misrepresentation. The following two subsections, embodied and operational carbon emanated from the interviews around the concept of ANZEH, illustrating that the participants had a distinct view between these two classifications of net-zero.

4.3.2.1 Embodied Carbon

Embodied carbon was described as the carbon emissions generated through construction which encompassed manufacturing, transporting, assembling a building and material replacements over the building's life cycle. It was indicated that in South Africa, there's no legislation promoting active reduction in embodied carbon and only a hand full of net-zero embodied buildings have been constructed:

> Participant 3: "*I think definitely operational carbon is seeing a much stronger focus and and from a legislation perspective and policy perspective, most of what's been spoken about is just operational carbon and there's no kind of direction in terms of embodied carbon really.*"

Participant 1 indicated that there are significant complexities associated with determining the factors and calculating embodied carbon. These challenges stem from the diverse typologies and materials used in the construction industry. This issue is not only prevalent globally but notably intricate and nearly unattainable within the context of South Africa. The lack of standardised tools and data availability for various building types and materials makes quantifying and certifying embodied energy a complex and demanding task. However, there are embodied carbon calculators challenging the market like OneClick LCA, but this is still difficult because if the inputs are not accurate then inconclusive results will be produced. These observations also allude to the above-mentioned lack of net-zero embodied buildings within South Africa.

Considering the above, the participants indicated that a developer can pursue a net-zero embodied house with the flooring, walling, roofing and other key housing elements being engaged to reduce the embodied carbon. Flooring was identified as a significant CO_2 contributor because of the high cement usage with cement composites not having a significantly reduced CO_2 footprint. South Africa uses clay bricks as their standard building material which can be substituted for hemp blocks or composite brick blocks. The usage of timber has experienced significant growth, as embodied carbon awareness increases. Participant 3 indicated that they had recently constructed a house with laminated timber and observed exceptional thermal properties alongside a reduced embodied CO_2 footprint. However, this alternative material came with a premium cost. Yet, the interviewee indicated that there has been a noticeable surge in both commercial and private residential projects utilising cross laminated timber, which suggests a broader rise in timber construction.

The challenges in managing embodied carbon, especially when using materials beyond traditional bricks and cement, persist, requiring specialised skills and techniques. The focus on reducing embodied carbon primarily targets materials such as cement and concrete in residential developments, while steel is a significant concern in commercial projects. Participant 3 emphasised the crucial consideration of the end-of-life cycle, especially concerning composite products. Composites, contain materials like plastic and rubber, or timber pose a recycling challenge once they reach the end of their life cycle. Unlike conventional brick and cement, which can be recycled and reused, composite materials often end up in landfills. Timber can be reused, but composite materials containing rubber lack recyclability options. This presents a substantial challenge, especially when considering the limited local capacity for materials and technology.

4.3.2.2 Operational Carbon

The interviewees expressed their understanding of operational carbon as CO_2 emissions generated from day-to-day operations. Operational carbon arises from the active use of a building's systems which includes all energy used for a household to function and remain comfortable. This encompasses the energy utilisation by lighting, heating, ventilation, and air conditioning (HVAC), hot water systems, and cooking (Participant 1, 3 & 4). It was noted that HVAC or air conditioning systems are not a common feature within South African affordable housing designs. Efforts aimed at reducing operational carbon should focus on these high consumption users before other energy user elements are optimised to limit financial spending while maximising energy savings.

The above approach to reducing energy consumption involves several strategies. Utilising energy-efficient lighting, such as LED technology, instead of incandescent or fluorescent bulbs. Another measure involves installing water flow rate fittings to minimise hot water usage. Additionally, employing alternative hot water heating methods like heat pumps or thermal solar geysers can significantly decrease energy consumption used to heat the water. The use of integrated design strategies must consider alternative energy sources like solar power, accounting for contextual factors like site location and climate specifics to maximise solar insulation (Participant 1).

Managing energy usage associated with cooking and appliances remains challenging due to household behaviour, but exploring solutions like using gas for cooking could be beneficial. Educating occupants about energy-efficient practices concerning cooking and appliance usage is pivotal for effective energy management. It's worth noting that lighting and hot water systems are typically responsible for the largest portion of energy consumption, however household behaviour will still drive their ability to reduce energy consumption (Participant 1 and 4). These mechanisms only focus on reducing energy consumption and to reach a net-zero energy goal, a house will have to off-set its overall energy consumption.

Participant 3 expressed that when aiming for net-zero energy operation, the role of renewable energy sources, particularly solar power or other alternatives, is fundamental. For ANZEH to achieve a net-zero energy goal, energy consumption must be offset either by on-site or off-site renewable energy production. Participant 4 expressed that achieving net-zero energy on-site is more feasible but still contingent on various factors. Available roof space, energy systems must be in place (such as battery storage), and energy efficiency systems play pivotal roles. While generating necessary energy from PV panels or solar hot water is plausible, cost becomes a key concern, particularly for affordable housing projects. Integrating PV or battery systems significantly escalates costs, prompting the need to strike a balance between functionality and affordability. Participant 4 further expressed their concerns around batteries, indicating that while they aid in load shedding and provide energy independence during non-solar periods, their inclusion escalates project costs considerably. Balancing cost-effectiveness with functionality becomes essential, possibly considering scaled-down battery systems for select components rather than comprehensive backup solutions. Finding cost-effective models that fulfil essential energy requirements while managing expenses is crucial for successful ANZEH initiatives.

Participant 1 noted that achieving net-zero energy solely on-site might not always be feasible, especially for high-density buildings or projects lacking ample roof space for direct implementation. Depending on these and other factors, achieving on-site net-zero status may vary across different housing typologies and household energy consumption habits. Therefore, large-scale solar or wind projects, managed by independent power producers, become essential in such scenarios. Wheeling energy from these off-site renewable energy projects to the intended site helps bridge the gap toward achieving net-zero energy goals. This process is not a direct solution but rather an exploratory process that is adapted based on the specific nuances of each ANZEH characteristics.

4.3.3 Affordable Net-zero Energy Housing Dimensions

4 critical NZEB characteristics (Technical, Economic, Social and Environmental Dimensions) were explored to transform a CAH to an ANZEH. The following 4 subsections will express the sustainable measures a developer or household may adopt within this framework to attain an ANZEH.

4.3.3.1 Technical Dimension

The technical dimension describes the physical housing features, passive energy efficient designs, building layout, materials, and construction techniques that will promote a building's sustainability (Chen *et al.*, 2017). The following emergent items resonated from the discussions such as passive designs, construction strategies, building modelling and legislative changes and their impacts on the industry.

All participants indicated that passive design strategies form the foundational elements in achieving efficient energy use. Participant 4 noted that the project team must invest time in comprehending various walling types, assessing different window sizes, selecting appropriate glazing, and determining the efficiency of overhangs. Modelling these elements from both thermal comfort and energy efficiency perspectives would yield substantial benefits and prevent construction overruns. Other mentioned design strategies revolved around well-thought-out site planning and context-specific considerations. These interventions encompassed a range of elements, including orientation, shading techniques, glazing, insulation, and roof reflectivity. Building orientation was considered a primary passive design because it plays a pivotal role in energy efficiency, especially in low-income housing scenarios like RDP homes. The utilisation of sunlight during winter months significantly reduces heating costs. While effective overhangs will reduce direct insolation during summer to reduce temperature levels within a home. These fundamental design aspects play a crucial role in minimising energy consumption and optimising the efficiency of a structure. Moreover, these passive design principles not only enhance comfort but also serve as indicators of high-quality homes contributing towards a home's marketability.

The integration of alternative building materials and construction methodologies presents a viable pathway to curtail a building's embodied carbon. One notable method involves the utilisation of demolition materials, particularly crushed rubble, recognised as a straightforward means to minimise embodied carbon during the initial construction phase. Participant 3 emphasised the potential of crushed rubble, specifically in non-structural applications like gabion walls, where aesthetic riverbed stones are typically visible, while hidden areas incorporate crushed building materials. However, employing such techniques presents inherent challenges and structural engineers must navigate the variance in aggregate properties when specifying grades for elements like concrete slabs, backfilling, or foundation layers. Additionally, Participant 2 proposed alternative aesthetic solutions such as opting for face bricks instead of plastering and painting. Although face bricks come with higher upfront costs, they deliver long-term advantages by eliminating the need for post-construction treatments or repainting, consequently reducing future maintenance expenses and mitigating additional embodied carbon growth. While the utilisation of composite alternative materials presents opportunities for enhanced structural, thermal, and aesthetic properties compared to traditional approaches, these materials often pose challenges. Participant 3 highlighted that such materials might lack recyclability or reusability, demand specialised skills for installation, or create difficulties during renovation. As a result, decisions pertaining to these materials necessitate early consideration in the project's life cycle, requiring proactive planning to address and navigate these challenges.

The interviewees acknowledge the importance of utilising software to model building operations during the design phase. Participant 1 and 2 both indicated that their professional teams use Revit, AutoCAD or SketchUp to model buildings from an architectural perspective. Participant 2 noted that they use the Edge App in the context of affordable housing to attain the ‘green’ certification acknowledgement linked to the tool. Additionally, the tool is affordable in terms of total intervention costs and certification fees. Certification involves three cost components: consultant fees, certifier fees, and the cost of interventions for compliance. Although EDGE has its glitches and operates as a somewhat opaque tool, it serves well for comparative analyses.

Participant 3 indicated that in South Africa, there are only a few software tools predominantly used for comfort and thermal analysis, such as IES (Integrated environmental solutions) and Design Builder. Participant 3 and 4 primarily utilised Design Builder for both energy and comfort modelling, with a primarily focus on thermal impacts and understanding the energy used for heating or cooling homes. However, it was noted that Design Builder is a more cost-effective software package, but IES can be integrated with Revit. Both participants emphasised the significance of modelling the comfort level in homes. They stressed that solely focusing on achieving low energy consumption without considering comfort will lead to uncomfortable living spaces. Prioritising comfort and health in building functionality is indispensable and ensuring spaces are both energy-efficient and comfortable for occupants, thus creating a healthy building environment. Participant 3 did indicate that for residential structures, these tools might be considered excessive since affordable housing generally doesn't consume substantial energy for heating and cooling.

Embodied carbon is modelled using OneClick LCA to comprehend the carbon impacts of construction materials. Participant 1 underscored the complexities and obstacles involved in accurately modelling the carbon footprint owing to the diverse range of material types, quantities used, and the limited availability of data. These challenges are pervasive globally, especially within the construction sector, and it proves nearly impossible within South Africa. Consequently, this participant suggested that in South Africa's construction industry, developers should prioritise operational sustainability over embodied sustainability due to the intricate nature of the field, making the latter considerably challenging to achieve.

The rate of sustainability adoption and drive is arguably driven by legislation and policy changes. There has been significant growth in sustainability awareness over the last few years, especially with the implementation of amended building standards like SANS 10400-XA. However, while this standard has transformed the market, it operates more as a compliance regulation rather than pushing the envelope toward advancing sustainability, unlike voluntary certifications like Green Star or EDGE (Participant 1). Most developers often focus on meeting the minimum compliance requirements to maximise profits:

> Participant 2: "*There are lots of ways and lots of developers are constantly looking at how to work around the legislation, so to still achieve it. But to achieve it efficiently and. It's it's often that balance between, you know, getting the regulations right and. You know, being efficient in the cost of the design.*"

Participant 1 indicated that despite the updates to SANS 10400-XA two years ago, it was not stringent enough and came after a prolonged wait of about 12 years. This delay and perceived leniency make it seem too little, too late. Thus, initiatives like Green Star and EDGE seem more effective in driving market transformation from the forefront, particularly EDGE, which integrates the financial world by collaborating with the International Finance Corporation (IFC). Through these collaborations, better development finance options, lower interest rates, and green home loans have been made available, promoting sustainable building practices in South Africa.

There are various avenues to enhance sustainability within the industry such as regulatory changes, voluntary rating systems, product standards, supply chain training, and fostering sustainable products through business incubators (Participant 4). Participant 3 noted that the push towards sustainability within affordable housing will not only arise from legislation, but also the impact of load shedding, and a growing marketing trend that promotes Green Star ratings as aspirational and "*feel-good endeavours*". These elements collectively create a "*perfect storm*", propelling the sustainability movement.

Implementing these initiatives could potentially have both positive and negative economic or social consequences within the South African context. On the positive side, companies adhering to sustainability standards could gain opportunities, while those unable to meet these standards might lose out on projects, potentially leading to job losses or retrenchments. This shift demands industry transformation to stay relevant and competitive. Additionally, challenges related to skill levels and qualifications might arise, necessitating skill imports and the local industry not being fit to handle such changes during rapid transition periods. Thus, while sustainability initiatives bring benefits, they also demand industry-wide adaptation and may affect employment and skills within the sector. Participant 3 noted that to promote sustainability in affordable housing there will need to be a supporting drive for alternate technologies, skill transfers within communities, and implementing a coherent sustainability framework for affordable housing deliveries.

4.3.3.2 Economic Dimension

Economic discussions were centred on analysing the financial impacts associated with various construction practices and operational strategies aimed at achieving both affordability and energy efficiency in homes. The focus was on evaluating the costs and financial implications involved in implementing alternative building methods and household operational approaches to facilitate ANZEHs that are not only cost-effective but also energy efficient.

Participant 2 emphasised the importance of assembling a cohesive team of consultants within any affordable housing project whether it is a house or a block of flats. Maintaining consistency within teams offers substantial benefits as it cultivates trust, familiarity, and efficient communication among team members. A consistent team dynamic minimises the learning curve associated with new collaborations, enabling greater productivity and a more streamlined workflow. This will prevent cost overruns, improve design cost efficiencies and support the sourcing of cost-effective materials.

Participant 3 expressed a similar sentiment, however within the sustainability space stating that when considering cost-effective sustainable development building materials, the method of construction significantly influences the process. Questions arise regarding whether on-site assembly, material transportation, prefabrication, or modular designs offer better cost efficiency. Addressing these concerns typically involves input from multiple project team members, including structural engineers, architects, and quantity surveyors, who often rely on tried-and-tested solutions. The importance of having a strong and coherent team will prevent delays and resolve uncertainties arising from alternative building materials. By the same token, the team members will be more willing to incorporate alternative or cost-effective building materials and/or designs stemming from their confidence within each other.

The above passages underscore the considerable financial impact of a proficient construction team and its capability to facilitate positive financial decisions. However, this synergy within the team extends from their social dynamics. Effective communication and adept educational skills within the team play a pivotal role in fostering unity among stakeholders. These interpersonal attributes not only aid in aligning decisions but also in nurturing a collaborative environment where parties synergise their efforts towards shared goals. This collaborative relationship will be further explored under the social dimension.

Conventional "innovative" building techniques, when employed in construction, can expedite building times, resulting in earlier project completion for homeowners. This acceleration will affect various aspects of the overall construction program, spanning from labour expenses and consultant fees to material costs. Participant 2 specified that the adoption of precast slabs and staircases has emerged as a cost-effective alternative to pouring concrete. These precast solutions significantly reduce construction time, allowing for faster completion of structures:

> Participant 2: "*…If you're putting up 100 square meter slab, for example, you'd have to build the formwork, you'd have to fix the steel, you'd have to pour the concrete… Then concrete gets to full strength after 28 days, but after seven days you can strip the formwork. Say your your length of time that it takes to put all of that up means that you're construction program of 80 months could be reduced to 14 months. So it means your monthly PNG and for you management of the site goes down by four months, which can be a substantial saving.*"

Participant 2 further articulated that they have explored other conventional materials like lightweight bricks or fire-resistant hebel bricks to reduce building weight, subsequently lowering foundation costs and expedites construction timelines because lighter bricks are easier to handle during construction. Participant 1 conveyed that using innovative strategies like incorporating crushed building materials into construction has been a practice they have employed since their initial project in 2011. This approach effectively upcycles waste materials, curbing embodied carbon, and economises expenses by negating the necessity to procure new materials.

The changing dynamics within construction materials have introduced a range of cost-effective alternative sustainable building materials. These materials are aimed at improving both embodied energy and thermal performance, surpassing the capabilities of conventional building materials. Among these alternatives, laminated timber stood out as a pivotal choice amongst the participants, showing the potential to reshape pre-conceived notions within the industry. However, despite its promising attributes, the recent surge in timber prices has hindered its immediate viability as a cost-effective option for affordable homes. Furthermore, the implementation of such materials necessitates the expertise of specialised consultants and developers that come at a cost premium. Participant 1 highlighted the potential use of composite materials, integrating recycled elements such as plastic, rubber, or timber. Such innovative integration can serve as substitutes for aggregates or could be incorporated into the composition of bricks. However, it's important to note that the cost implications could vary based on the manufacturing technique or the specific material substitutes employed. Depending on these factors, the cost of the materials could either decrease or increase, thus influencing the financial aspects of alternative materials. Furthermore, these materials may not be reusable at the end of a house's life cycle and might require additional costs to dispose of in comparison to conventional building materials, thus inhibiting the financial benefits derived from avoiding the purchase of new materials.

Before considering alternative or composite building materials it is important to recognise that traditional construction methods and materials offer a straightforward and cost-effective approach to reducing construction expenses. Strategies focused on optimising construction processes and material usage play a significant role in promoting cost savings within the context of affordable housing. In some cases, these conventional approaches may be more beneficial than sourcing low embodied carbon materials.

From a household operational financial perspective, hot water was the main energy consumer expressed by all the participants followed by lighting and cooking. Heating and cooling were also expressed as high energy consumers, however these systems are not commonly built into affordable homes.

Participant 1 highlighted the substantial influence of water usage on hot water consumption, directly correlating to the electricity bill. Implementing straightforward measures such as optimising faucets in key areas like the kitchen, bathroom basins, and shower can significantly impact water heating expenses without necessitating extra costs. Water-saving faucets or integrated flow rate attachments typically cost the same as non-water-saving faucets. Moreover, these interventions not only curtail heating costs but also contribute to lowering the overall water bill. These sustainable initiatives are primarily propelled by the conscious thinking and influence of the project team, extending beyond mere cost considerations to encompass the broader aspects of socioeconomic benefits and the cost of occupancy. Participant 3 indicated that implementing alternative domestic hot water heating systems offers a direct way of cutting down on hot water heating expenses, nevertheless, they involve a relatively high initial capital expenditure to install. While households can expect a return on investment over time, the upfront cost might be prohibitive, particularly for those in lower-income brackets. For this reason, it was further recommended that households should rather invest in thermal solar energy solutions over PV heating solutions because of their significantly lower capital cost.

Artificial lighting has seen significant market transformations which has led to the evolution of lighting technologies like LEDs becoming cost effective lighting options, with incandescent and compact fluorescent lamps being phased out. The costs of these eco-friendly alternatives have substantially decreased over time with their operational life improving over incandescent bulbs and compact fluorescent lamps. This shift in the market landscape encourages competition, driving prices down and offering a wider range of affordable choices.

No alternative cooking methods arose from the discussion to reduce a households energy cost. However, it was noted that a household should be educated in their appliance usage, and the impact this will have on their energy bill. In affordable residential homes, heating and cooling systems are typically not integrated into the construction due to cost-cutting measures. Consequently, households resort to using standalone heating and cooling appliances during specific seasons, substantially adding to their energy expenses. However, addressing this issue doesn't necessarily require extra expenditures; instead, it involves strategic planning, optimising building orientation, and implementing effective insulation methods, all of which are relatively cost-effective measures:

> Participant 3: "*You know, people plug in heaters and their homes in winter and and in that case it doesn't cost you anything to reduce that. You know, it's just about planning better orientating your building North you know those kind of things. Insulation is very cheap really. So no cost impact there…*"

The above passages have expressed the financial concern surrounding the capital and operational cost implications of ANZEH. Despite the numerous cost effective energy saving initiatives available to households, there remains a financial concern around the high capital cost of water heating solutions, construction techniques and alternative building materials. The interviewees iterated that the adoption of sustainable building practices and operations can facilitate the unlocking of green financing options through banks, which offer better interest rates for residential projects. The IFC's involvement has significantly influenced South Africa's financial landscape by leveraging connections with major financial institutions to introduce green bonds, finance, and enhanced sustainable development funding.

The participants further iterated that accessing green financing options for sustainable projects can be challenging, especially for smaller developers compared to larger players, who possess more leverage with financial institutions. Participant 1 suggested that smaller construction firms or individual home purchasers may struggle to access these advantages, because these schemes are often tailored towards larger companies. Further, the current green bond setup tends to favour bulk certification schemes, making it challenging for smaller developers or single homes to qualify for the more favourable interest rates offered by green home loans. Certification fees, which don't scale proportionally per unit, create financial hurdles for smaller projects, whereas larger developments can benefit from economies of scale.

Participant 3 expressed a similar sentiment, indicating that there seems to be a barrier preventing easier access to green bonds or financing options for smaller developers or individual homeowners, possibly due to banks being slower in developing products for the individual consumer:

> Participant 3: *"…I think it may just it may be that the banks haven't necessarily created those products yet in the consumer space… And I think banks are only now starting to sort of put across consumer products. That's why I think the delay has been that the products haven't been developed by the banking industry."*

Noting the above green financing challenge, it is evident that large developers currently enjoy improved access to favourable bonds within the sustainable sphere. Initiatives like Edge are supported by the IFC through the World Bank which has long emphasised climate and green finance for commercial developments. Consequently, Edge projects can leverage these financing opportunities, securing improved interest rates. However, this approach is not as feasible or accessible for small developers or individual homeowners due to scale limitations and certification fee costs.

4.3.3.3 Environmental Dimension

The primary motivation for sustainable initiatives is financial returns, with the environmental impact following closely. An intriguing observation was the interconnectedness of financial and environmental impacts, wherein installing energy-efficient fittings to diminish energy consumption, resulted in decreased operational CO_2 emissions and reduced energy procurement needs because less energy was consumed.

From a construction perspective, components such as bricks, mortar, foundations, steel, and finishes, contribute to the overall CO_2 emissions of a home. Participant 2 indicated that straightforward and traditional construction approaches can help mitigate CO_2 emissions, without relying on intricate material composites or advanced building methods. For instance, incorporating precast slabs into construction practices minimises material wastage. These slabs can be manufactured to thinner dimensions than concrete pours, thus further conserving materials and subsequently reducing embodied energy. This becomes important particularly for concrete as it is known for its high embodied carbon content. Further conventional techniques involve utilising hollow bricks, requiring less material, or employing hebel bricks that eliminate the necessity for additional fire-resistant insulation, along with the use of demolition materials for infills or recycling building materials (Participant 1 and 2). These approaches effectively reduce both the quantity of construction materials used and the associated embodied energy.

Alternative embodied energy reduction approaches employ integrating recycled materials into conventional building elements. This seeks to create composite materials with improved embodied energy and thermal properties. Laminated timber stood out as a new upcoming building material within South Africa to significantly reduce embodied carbon. Moreover, it weighs less than steel and concrete, leading to a reduced requirement for reinforcement in foundations, further contributing to the reduction of embodied carbon. This approach will significantly reduce the embodied carbon footprint of buildings, providing an opportunity to cut down on the environmental impact of using virgin materials, and create a sustainable solution for future building practices. However, it was emphasised that when addressing a building's life cycle these materials might not be reusable and will have to be sent to a landfill. Consequently, developers or homeowners may find it challenging to offset the embodied carbon at the end of a building's life through up-cycling. This dilemma poses a significant challenge for developers striving to create net-zero embodied carbon projects.

Alternative hot water heating solutions like solar or thermal heating systems can nearly mitigate the need for grid tied power. It was recommended that a homeowner seeking to install solar panels for household energy production should invest in heat pumps to maximise roof space for PV cells. Given sufficient roof space, going entirely for solar PV to electrify a home, incorporating efficient electrical systems for cooking and heating water, could be a practical choice. For homeowners operating on a budget, thermal solar heating systems are suggested as a more cost-effective alternative compared to a PV system. Participant 3 noted that solar thermal panels can reach a 70% efficiency compared to around 15% for solar PV panels in extracting energy from the sun, however thermal solar systems tend to have higher maintenance and life cycle costs.

The role of renewable energy sources, particularly solar power, in achieving the net-zero energy operational goal was highlighted by participant 4. Participant 4 further suggested that many homes might need to rely on offsetting energy due to limitations in achieving net-zero energy solely through on-site renewable energy production. Factors like limited roof space, especially in high-density apartments, often restrict on-site net-zero energy goals. Therefore, large-scale wind or solar projects located elsewhere are crucial, enabling the wheeling of energy into projects to reach net-zero energy.

For single residential houses, achieving net-zero on-site is more feasible depending on factors like available roof space, existing energy systems, and the presence of storage like batteries compared to apartments. Batteries play a pivotal role in addressing a significant drawback of PV systems, which cannot generate power during periods without sunlight, such as in the evening. However, residential houses pose a challenge because solar power is generated during the day, while the main energy consumption periods for households typically occur in the morning and evening. Participant 4 highlighted that although batteries offer benefits, their cost implications might label them as a luxury. To manage costs, models could involve scaling down the batteries or selectively applying them to specific systems rather than across the entire household. Consequently, integrating PV panels and batteries for on-site power generation and offsetting CO_2 generated power will raise overall costs, potentially creating affordability challenges.

4.3.3.4 Social Dimension

Considering the energy-centric nature of ANZEH, their success in development, delivery, and operation hinges significantly on the social aspects of stakeholders. The interviewees emphasised that the sustainable knowledge of the client, homeowner, consultants, professional teams, and contractors will ultimately drive the delivery of ANZEH. Participant 3 noted that in high-income sectors, there's often a trend-driven demand for green solutions, whereas in lower-income segments, it's more about meeting national requirements for inclusive housing and sustainability standards. Moreover, the GBCSA and Edge sustainability rating tools also plays a vital role by exposing contractors and suppliers to sustainable approaches, creating a ripple effect across various projects. However, these tools are often perceived as luxuries, and low-income housing projects typically veer away from such sustainability standards, focusing solely on meeting the basic legislative requirements.

The level of sustainability awareness amongst stakeholders were summarised into three levels by participant 4. Firstly, there's a committed and transparent group that confidently discusses sustainability and actively seeks to drive the development of sustainable homes. The second group tends to embrace 'greenwashing,' portraying eco-friendly images without substantial backing. These individuals might invest or implement basic sustainability concepts to attract a “green” image. Lasty, there is the group that is disinterested in sustainability and solely focused on selling a product to net maximum returns.

Unpacking the sustainable and net-zero development approaches revealed the intricate relationship between construction professionals such as the design teams, management teams, and contractors, who influence a building's successful delivery. Participant 4 emphasised the importance of transferring design intent accurately from the professional team to the construction contractors. Misinterpretations or misunderstandings during this process can lead to errors or incomplete work that affects the overall construction quality and costs. Additionally, the successful transfer of information from the construction team to the operators or homeowners is equally vital. This transfer of knowledge and understanding allows for the proper operation of the space as intended, ensuring that the building functions optimally, to achieve the preconceived operational efficiency standards.

Participant 2, a specialist in affordable and social housing, emphasised the universal desire for a return on investment as a foundational aspect in any housing venture. Even organisations like [Company name redacted], aiming for affordable and social housing solutions, must consider financial returns to sustain their operations. However, the participant noted that some people are more inclined toward civic-mindedness and might prioritise affordable housing despite lower profit margins:

> Participant 2: “*…So even [Company name redacted] needs a return on investment. Otherwise, we can't keep the whole business going, so there are people though, who are more civically minded and will want to do affordable housing for a lower margin.*”

This observation indicates that the feasibility of a project will take preference over a building’s level of sustainability. Nevertheless, participant 2 indicated that this provides an opportunity for government intervention in setting alternative standardised ANZEH requirements and linking these requirements to subsidies. This could foster the supply of affordable housing, while simultaneously promoting sustainable developments and living. It is essential to expedite the provision of social and affordable housing to address the growing housing issues caused by an increasing population and the slow rate of housing development.

Participant 3 did critique the potential economic, environmental, and social consequences associated with the development of sustainable buildings. A study conducted by their team, of a green retrofit project, showed inefficacies due to inadequate support and maintenance of installed sustainability products, such as solar water heaters and ceiling materials. These shortcomings led to malfunctions because the residents did not have the required mechanisms to replace or repair the damaged products. Participant 3 further emphasised the importance of embedding alternative building materials into communities to facilitate local builders' familiarity and utilisation of these products. Skill development and knowledge transfer were highlighted as a crucial shortfall which had unintended consequences of disempowering homeowners from their residences.

ANZEH framework was critiqued by participant 3, who noted, that if only the sole focus was on achieving net-zero carbon emissions, one might overlook the broader scope of sustainability, which encompasses various aspects crucial to people's well-being. Social elements such as transportation, even though it's harder to influence at a building level, plays a pivotal role in affordability. Aspects such as access to food, the internet, and employment opportunities are encompassed within the domains of sustainability and affordability. These factors highlight the considerable social impact of comprehensive sustainability initiatives beyond achieving net-zero emissions. Participant 4 highlighted the long-term outlook of ANZEH on reducing South Africa’s built environment carbon footprint and pressure on the national energy grid. Moreover, at the micro-economic level, the financial benefits for homeowners could potentially result in elevated disposable income and improved living standards.

4.3.4 Attributes and Characteristics of an ANZEH

Table 4.2 summarises the attributes and characteristics of ANZEH identified through the qualitative analysis. This table outlines the various building elements and their associated technical specification that contributes to ANZEH. Each entry details the impact of the technical specification, including whether it involves conventional construction techniques, its affordability for implementation, and its effect on embodied carbon, operational carbon, or both types of carbon emissions.

Technical specifications marked with asterisks were not evaluated in the reviewed literature but emerged during the interviews, highlighting additional strategies for achieving ANZEH.

The information presented will guide the subsequent quantitative modelling process, which aims to estimate the embodied and operational carbon impacts of incorporating these techniques and building elements.

Table 4.2: ANZEH attributes and characteristics summarised

Building Element	Technical Specification	Impact	Construction Method		Financial Impact		Carbon Emissions	
			Conventional	Innovative	Affordable	Expensive	Embodied	Operational
Passive Design	Building modelling*	Create virtual model of building to evaluate expected embodied and operational carbon		✓	✓		✓	✓
Passive design	Building orientation	Optimise indoor thermal environment	✓		✓		✓	✓
Passive design	Cost effective finishes*	Limits capital cost for homeowners	✓		✓		✓	✓
Passive design	Design for longevity*	Minimise maintenance costs	✓		✓		✓	✓
Passive design	Efficient housing design*	Maximise liveable area in a cost-effective manner	✓		✓		✓	✓
Market Strategy	Green bonds	Improved finance options and lower interest rates.		✓	✓		✓	✓
Passive design	Legislation and policies*	Mandatory sustainable built environment policies will drive “green” initiatives.	✓			✓	✓	✓
Passive design	Strong professional team*	Prevents miscommunication and promotes consistency	✓		✓		✓	✓
Passive design	Property location	Access to public transport, schools and employment opportunities	✓		✓		✓	✓
Passive design	Composite material*	Reduce embodied carbon, but might not be re-cyclable at end of life		✓		✓	✓	
Passive Design	Face brick finish*	Exterior walls are not plastered and painted to reduce maintenance costs	✓			✓	✓	
Passive Design	Hollow bricks*	Lighter than conventional bricks – Reduces foundation costs and construction times.	✓		✓		✓	
Passive design	Laminated timber*	Reduced embodied carbon and improve thermal properties		✓		✓	✓	
Passive Design	Recycle demolition materials*	Re-use demolition materials in non-structural applications to reduce embodied carbon	✓		✓		✓	
Passive design	Precast elements*	Precast building elements will reduce construction time, material usage and waste.	✓		✓		✓	
Passive Design	Shading techniques	Installation of overhangs to limit indoor direct insulation	✓		✓			✓
Passive Design	Glazing	Reduces heat gain from direct insulation and heat loss during cold periods	✓			✓		✓
Passive Design	Insulation	Improves indoor environmental thermal comfort.	✓		✓			✓
Passive Design	Roof reflectivity*	Paint a roof white to minimise heat absorption	✓		✓			✓
On-site Renewable	Energy offset	Non-renewable energy consumption must be offset by renewable energy production		✓	✓			✓
Electrical Storage	Energy storage	Stores renewable energy for non-solar hours.		✓		✓		✓
Off-site Renewable	Energy wheeling	Purchaser of renewable energy instead of non-renewable energy for consumption		✓	✓			✓
Energy Management	Heat pump	Heat pump will reduce electrical energy required to heat hot water	✓			✓		✓
Psychological Strategies	Household education	Educating individuals about energy efficient behaviours and how to reduce appliance energy usage.	✓		✓			✓
Fixtures	LED	Reduce energy usage	✓		✓			✓
Energy Management	Thermal geysers	Thermal geyser will reduce electrical energy required to heat hot water	✓		✓			✓
Water fitting	Water flow rate fittings	Reduce consumption of hot water, thus less energy will be required to heat hot water.	✓		✓			✓

4.4 Quantitative Analysis

This section seeks to demonstrate the various sustainable techniques and building materials that can be implemented to achieve an ANZEH. Findings from the qualitative analysis were used to guide the embodied and operational energy modelling. This section begins with presenting the ANZEH scenario, followed by an overview of the implemented sustainability components, calculations and analysed embodied and operational energy results.

4.4.1 Affordable Net-zero Energy House Case Structure

A 3-bedroom house base case was use because it was identified as a common housing typology in South Africa. The house plan was transposed into Revit and displayed in Figure 4.1 and Figure 4.2 provides a three-dimensional render of the house.

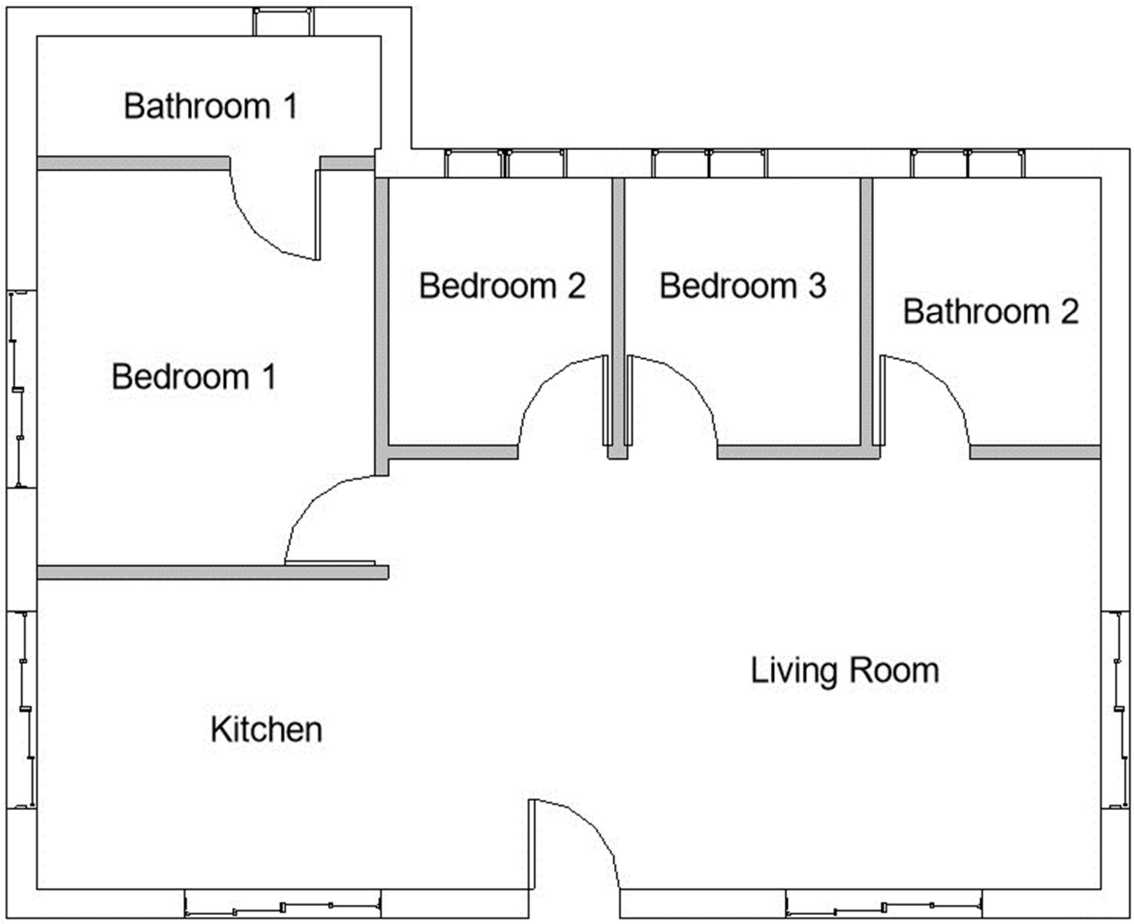


Figure 4.1: Affordable 3-bedroom house floor plan

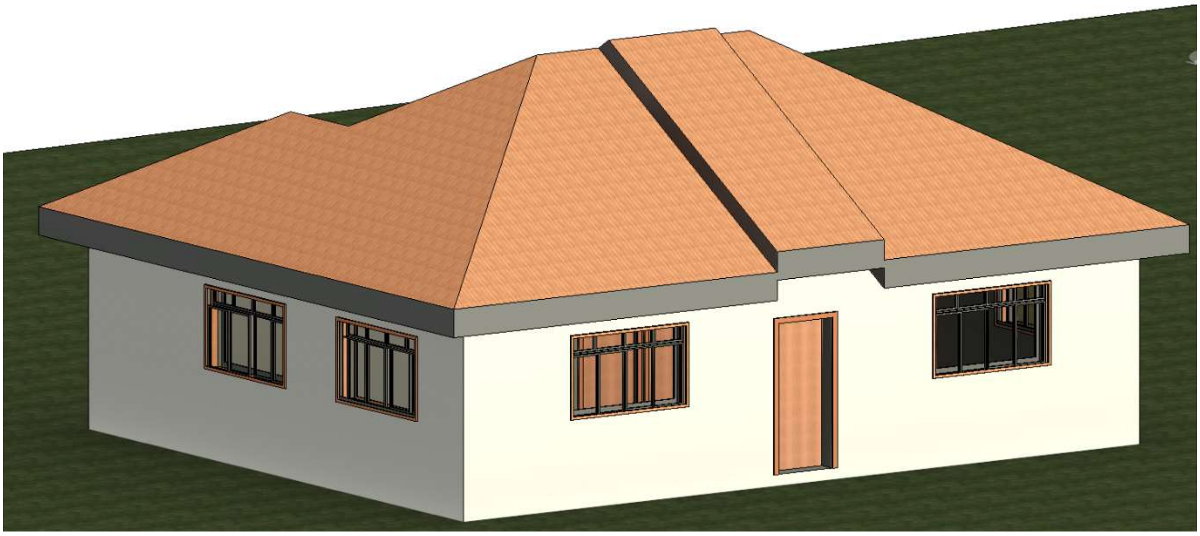


Figure 4.2: 3D model of the 3-bedroom affordable house

The house is free-standing, consisting of 3-bedrooms, a living room, a kitchen, a bathroom and an attached water closet room, whose size specifications are presented in Table 4.3 below.

Table 4.3: Room dimensions

Typology Element	Area (m^2)	Area Ratio
Kitchen	14	16%
Living Room	36	40%
Bedroom 1	15	17%
Bedroom 2	17	8%
Bedroom 3	7	8%
Bathroom 1	5	6%
Bathroom 2	6	7%
Lettable Area	**90**	**100%**

The house is orientated in a North facing direction to maximise sunlight exposure and in accordance with SANS guidelines. The foundation rests on strip footing, and the external façade comprises a clay-brick half wall. Moreover, the wall has been plastered and painted. The internal walls are half brick composed of clay bricks, plaster and painted. The floor is concrete with a linoleum finish, the doors and windows (Single glaze) are wooden, and the roof comprises of wooden trusses with clay tiles.

This base case's energy performance served as the foundation for three ANZEH scenarios, and by extension the benchmark for evaluating the scenarios. Each scenario introduced varying degrees of energy-saving strategies, with the aim of reducing energy demand and, by extension, carbon emissions.

Scenario 1 represented an entry-level ANZEH, incorporating basic energy-saving measures accessible to developers and utilised conventional construction techniques which follows the cost and material reduction techniques expressed by Participant 2. Additionally, easily available energy reducing materials and fixtures were incorporated to reflect an entry level ANZEH. This scenario sought to accommodate the lack of skills, expertise and knowledge of sustainable techniques, materials and technologies, highlighted by the interviewees. Simple embodied energy reduction methods were used such as 10% fly ash in ready-mix concrete, hollow bricks to construct walls, and, limiting painting to only the interior walls. Additionally, leaving exterior walls bare mitigates the accumulated embodied energy gained with repainting a building over its lifespan. These construction materials with other simple energy reduction techniques such as using compact fluorescent light bulbs and the adoption of a thermal solar geyser reduced Scenario 1's carbon emissions.

Scenario 2 sought to blend conventional building techniques with a few innovative embodied and operational energy reducing techniques. This method was selected for developers who have begun to embrace new construction methodologies and are familiar with the principles of sustainable development. These materials encompassed insulating the floor with cellular insulation, installing hot water flow rate fixtures (Participant 1), utilising cross laminated timber external and internal walls, adopting a monologic roof system, using 30% fly ash ready-mix concrete, and switching wooden single glaze windows to double glaze aluminium windows. The installation of double glaze windows resulted in higher embodied carbon emissions, however, the expected operational energy savings outweighed the additional embodied emission. Operational energy followed the same modelling as Scenario 1 except, scenario 2 had 50% solar energy production. The solar system was configured to supply 1,500 KWh which utilised 450W panels (Marthinusen, 2023). The following equation was utilised to determine the solar system size: kW system = Daily kWh usage / Average daily peak sunlight hours * 1.25 (Efficiency factor) (Next Renewable Generation, 2023). This resulted in the following calculation and output: (2,935kWh per annum / 12 / 30) / 4.7 (Western Cape peak sunlight hours per day (Climatebiz, 2023)) * 1.25 = 2.17kW system. Therefore, a 3kW system sized specification was utilised and occupying approximately 12m^2 of roof space.

Scenario 3 models a scenario where all energy saving construction techniques, materials and technologies have been embraced to achieve an ANZEH. This approach assumes that a developer or homeowner is well versed in sustainable development and the utilisation of alternative buildings materials or sustainable technologies. The construction technique followed Scenario 2 except the external and internal walls utilised autoclaved aerated concreate solid blocks, and the addition of re-used EPS insulation in the cavity walls to enhance insulation as well as the adoption of energy efficient appliances. Further, a wooden roof truss, hemp cladding tile system, with cellulose ceiling insulation, was adopted. The operational energy parameters remained consistent with those of Scenario 2, but all electrical energy will be generated by on-site solar systems. The solar system was configured to supply 3,600 kWh which utilised 450W panels (Marthinusen, 2023). The following equation was utilised to determine the solar system size: kW system = Daily kWh usage / Average daily peak sunlight hours * 1.25 (Efficiency factor) (Next Renewable Generation, 2023). This resulted in the following calculation and output: (3,600kWh per annum / 12 / 30) / 4.7 (Western Cape peak sunlight hours per day (Climatebiz, 2023)) * 1.25 = 2.6kW system. Therefore, a 3kW size system was utilised, occupying an estimated 12m^2 of roof space.

The Tables 4.4 and 4.5 below summaries the modelling parameters used within the OneClick LCA and Edge App software's. Each table outlines key inputs related to construction materials, energy consumption, operational efficiency, and carbon emissions, which are crucial for assessing both embodied and operational carbon.

Table 4.4 indicates the embodied materials used by the base case and scenarios.

Table 4.4: OneClick LCA material input parameters

Element	Base Case (Conventional)	Scenario 1	Scenario 2	Scenario 3
Strip footing	Concrete	Ready-mix concrete - 10% fly ash	Ready-mix concrete - 30% fly ash	Ready-mix concrete - 30% fly ash
External wall	Solid terracotta half brick wall (110mm)	Hollow terracotta half brick wall (110mm)	Cross laminated timber (80mm)	Cavity autoclaved aerated concrete solid block wall with EPS insulation recycled panels (250mm)
Internal wall	Solid terracotta brick wall (110mm)	Hollow terracotta brick wall (110mm)	Cross laminated timber (60mm)	Gyproc Rhinoboard (Gypsum plasterboard) on wooden frame (76mm)
Exterior and interior walls painted	Alkyd emulsion-based paint	Only interior painted - Alkyd emulsion-based paint	Only interior painted - Alkyd emulsion-based paint	Only interior painted - Alkyd emulsion-based paint
Floor slab	Concrete slab	Concrete slab – 10% fly ash	Concrete slab – 30% fly ash	Concrete slab – 30% fly ash
Floor	Linoleum finish	Ceramic glazed tile	Cellular glass insulation with ceramic glazed tile	Cellular glass insulation with laminated flooring
Ceiling	Particleboard	Gypsum ceiling boards	No ceiling	Gypsum ceiling boards
Roof	Wooden roof truss, clay tiles with rock wool insulation	Wooden roof truss, clay tiles with rock wool insulation	Monologic roof system – Cross laminated timber	Wooden roof truss, hemp cladding tiles with cellulose insulation
Windows	Steel frame & single glaze	Wooden frame & single glaze	Wooden frame & double glaze	uPVC frame & double glaze
Doors	Wooden	Wooden	Wooden	PVC

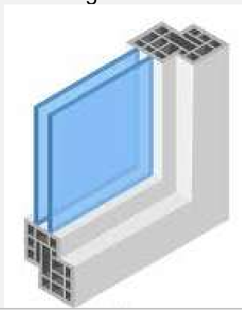
Table 4.5 indicates the operation energy scenario parameters inputted into Edge.

Table 4.5: Edge App material and technological parameters

Sustainability Component	Scenario 1	Scenario 2	Scenario 3	Pictures
		Energy Efficient Measures		
Reflective roof	✗	0.61	0.53	*Reflective roof 
Natural ventilation	✓	✓	✓	
Domestic water heating system	Thermal solar geyser	Thermal solar 150L geyser	150L geyser	*Thermal solar geyser 
Lighting	Compact fluorescent bulb	LEDs	LEDs	*LED light 
Electrical smart meter	✓	✓	✓	*Smart electrical meters 

On-site renewable energy production	0% annual energy consumption	50% annual energy consumption	100% annual energy consumption	*Photovoltaic roof system 
		Water Efficient Measures		
Water efficient shower heads	✘	4L/min	4L/min	*Aerated shower head 
Bathroom sink water efficient faucet	✘	6L/min	6L/min	*Aerated sink fitting 
Kitchen sink water efficient faucet	✘	6L/min	6L/min	*Aerated sink fitting 
		Materials		
Floor finish	✘	Linoleum Finish	Linoleum Finish	*Linoleum floor finish 

Roof	Clay tile on timber rafters	Cross laminated timber	Hemp cladding on timber rafters	*Clay tile on timber rafters 
External walls material	Brick wall internal and external painted	Cross laminated timber	Autoclaved aerated concrete solid block wall exposed and internal painted	*Aerated concrete solid block wall 
Internal walls	Terracotta brick wall	Cross laminated timber	Autoclaved aerated concrete solid block wall	*Cross laminated timber 

Window frames	Wooden	Aluminium	uPVC	*uPVC Window 
Window glazing	Single	Double	Double	*Double glaze window diagram 
Roof insulation	Rock wool insulation	✘	Cellulose insulation	*Cellulose insulation 

External wall insulation	Air gap	Air gap	EPS insulation	*EPS insulation 
Floor insulation	✘	✘	Cellulose insulation	*Cellulose insulation 

The preceding discussion highlighted the primary deviations between the base case and the various scenarios. The following paragraphs will outline how Scenario 1's LCCE was calculated.

Initially, the Revit building plan was uploaded to OneClick to capture the building materials and quantities. The building materials in OneClick were updated based on South African information, except for the uPVC window frame parameter. There was no carbon emission data for this parameter and OneClick's UK uPVC window frame dataset was utilised. Additionally, material transportation distances were manually inputted by measuring the distances, using Google Maps, between various material sources and the development site. These parameters enabled the software to generate the CO_2e emissions for Modules A1 - A5.

Modules B1 – B5 were calculated manually, with Module B1 set to zero, as carbon absorption was not measured in this research. Due to the unavailability of operational and maintenance guides, the carbon emissions for maintenance (Module B2) were computed by multiplying 40kgCO_2e/m^2 by the gross internal area. The emissions for repair (Module B3) were determined by summing 25% of the product of Module B2 and 10% of the product of Module A1-A3. The emissions for Modules B4 - B5 were calculated using the expected service life of materials, as specified in the RICS Whole Life Carbon Assessment for the Built Environment guide. For instance, hardwood windows have an expected lifespan of 30 years, while the building lifespan adopted in this research was 60 years. Therefore, the carbon emissions from windows amounted to 1,180kg CO_2e, which was then multiplied by 2 to determine the B4 – B5 emissions, resulting in 2,360kg CO_2e. This process was repeated for each individual building element.

The emissions for Module B6 were calculated using the Edge App software. The building's dimensions and specifications were uploaded to the App, and South Africa's electricity emission factor of 1.013kg CO_2e/kWh was applied to convert kilowatt-hours to carbon emissions (Department of Forestry Fisheries and the Environment, 2024). The software then generated a monthly estimate of 0.33 tCO_2e, which was annualised and forecasted over the building's 60-year lifespan. Module B7 and B8 were not examined within the scope of this thesis.

Modules C1–C4 and D1, Module D2 utility exports were assumed to be zero for the purposes of this research, were modelled using OneClick LCA, which operates under several key assumptions. The program assumes standard demolition and deconstruction practices, incorporating typical machinery and techniques suitable for the building type and material composition. Additionally, the model allows users to specify the waste processing method for the different building materials. For instance, in Scenario 1, conventional building waste practices were adopted, with construction materials modelled as landfilled, while items such as wood and glass were recycled. Further, the program accounts for energy use and efficiency at recycling facilities and considers typical disposal methods, including emissions from material incineration.

4.4.2 Cross Scenario Analysis Overview

A clear link between the level of ANZEH and a reduction in whole LCCEs emerged from the findings. However, the weighting of carbon emissions though out a scenario's life cycle varies. The base case generated the highest LCCEs (560,091kg CO_2e) LCCE, followed by Scenario 1 (491,920kg CO_2e), then Scenario 2 (270,719kg CO_2e) and Scenario 3 (35,915kg CO_2e). This LCCE decreasing trend follows the improved level of ANZEH attributes. Table 4.6 provides a summary of each case LCCEs.

Upon initial evaluation, Scenarios 1 and 2 outperformed Scenario 3 in terms of embodied carbon emissions across Modules A1-A5, as indicated by the green highlights. All scenarios, however, exhibited identical outcomes in Modules B1-B3 and D2, denoted by the blue highlight. Modules B3-B6 presented more variability; Scenario 1 achieved the greatest reduction in CO_2 emissions across all these modules, whereas Scenario 2 demonstrated reductions in B3 and B6 only, and Scenario 3 achieved savings exclusively in B6. Notably, only Scenario 2 exceeded the base case in Modules C1-C4, marked by the red highlight. Conversely, Scenario 1 was the only case to decrease carbon emissions relative to the base case in Module D1.

Table 4.6: Whole life cycle carbon emissions assessment for the 3 ANZEH scenarios

Whole Life Cycle Carbon Emissions For 3 Varying Levels of ANZEH					
Module	**Category**	**Base Case (kg CO2e)**	**Scenario 1 (kg CO2e)**	**Scenario 2 (kg CO2e)**	**Scenario 3 (kg CO2e)**
A1-A3	Construction material	10 629	9 521	4 748	12 155
A4	Transport to site	653	634	503	398
A5	Construction and installation process	976	895	754	519
A1-A5	**Upfront Carbon**	**12 257**	**11 051**	**6 005**	**13 072**
Variance (%)		**-**	**-10%**	**-51%**	**7%**
B1	Use	-	-	-	-
B2	Maintenance	2 400	2 400	2 400	2 400
B3	Repair	1 663	1 552	1 075	1 815
B4-B5	Material replacement and furbishment	7 554	6 294	23 426	20 142
B6	Energy consumption	532 800	468 000	230 400	0
B1-B6	**In-use**	**544 417**	**478 246**	**257 301**	**24 357**
Variance (%)		**-**	**-12%**	**-53%**	**-96%**
C1-C4	End of life	3 906	3 096	9 592	652
C1-C4	**End of Life**	**3 906**	**3 096**	**9 592**	**652**
Variance (%)		**-**	**-21%**	**146%**	**-83%**
D1	External impacts	-489	-473	-2 179	-2 167
D2	Utility Exports	-	-	-	-
D1-D2	**Information beyond construction works life cycle**	**-489**	**-473**	**-2 179**	**-2 167**
Variance (%)		**-**	**-3%**	**345%**	**343%**
Total		**560 091**	**491 920**	**270 719**	**35 915**
Savings		**-**	**-12%**	**-52%**	**-94%**

*Green highlights indicate the case study performed better than the base case.

*Blue highlights indicate the case study performed the same as the base case.

*Red highlights indicate the case study performed worse than the base case.

Focusing on the upfront embodied carbon emissions attributed to material production, transportation, construction and installation. The construction material carbon emissions were the largest contributor across all scenarios, averaging 83% of the total emissions for module A.

In Scenario 1, upfront carbon emissions decrease to 11,051kg CO_2e, reflecting a 10% reduction compared to the base case. This decrease is primarily due to optimisations in conventional construction materials, such as incorporating 10% fly ash in ready-mix concrete, utilising hollow bricks for walls, and restricting painting to interior walls only. These measures resulted in a reduction of 1,206kg CO_2e in carbon emissions. Carbon emissions attributed to transportation, construction and installation marginally decreased because conventional construction techniques were adopted.

Scenario 2's, upfront carbon emissions decreased to 6,005kg CO_2e, representing a 51% decrease compared to the base case. The adoption of laminated timber resulted in a potential global warming biogenic 9,397kg CO_2e sequestration, and the monologic roof system resulted in the further reduction of building materials. However, the inclusion of solar panels constituted an additional 4,680kg CO_2e embodied emissions, leading to a construction material emission of 4,748kg CO_2e (Module A1-A3). Transport and construction carbon emissions reduced by 23% because lighter and less materials were used.

Scenario 3's carbon emissions exceeded the base case by 815kg CO_2e. The use of autoclaved aerated concrete solid block, hemp cladding instead of tiles resulted in 8,375kg CO_2e of construction material. The inclusion of solar panels resulted in the construction material emissions exceeding the base at 12,155kg CO_2e (Module A1-A3). Carbon emissions attributed to transportation decreased by 40% and construction carbon emissions diminished by 50%. The reduction in both modules was driven by the substitution of heavier materials with lighter alternatives, such as autoclaved aerated concrete solid blocks and hemp cladding.

Carbon emissions attributed to transportation, marginally change between the base case and scenario 1. This trend arose due to both scenarios adopting similar construction materials. However, Scenario 2 and 3's transport emissions decreased due to the use of lighter materials.

These scenarios illustrate the impact that different material choices have on managing embodied emissions. Figure 4.3 illustrates the carbon emission percentage difference between the base case and the scenarios for upfront carbon.

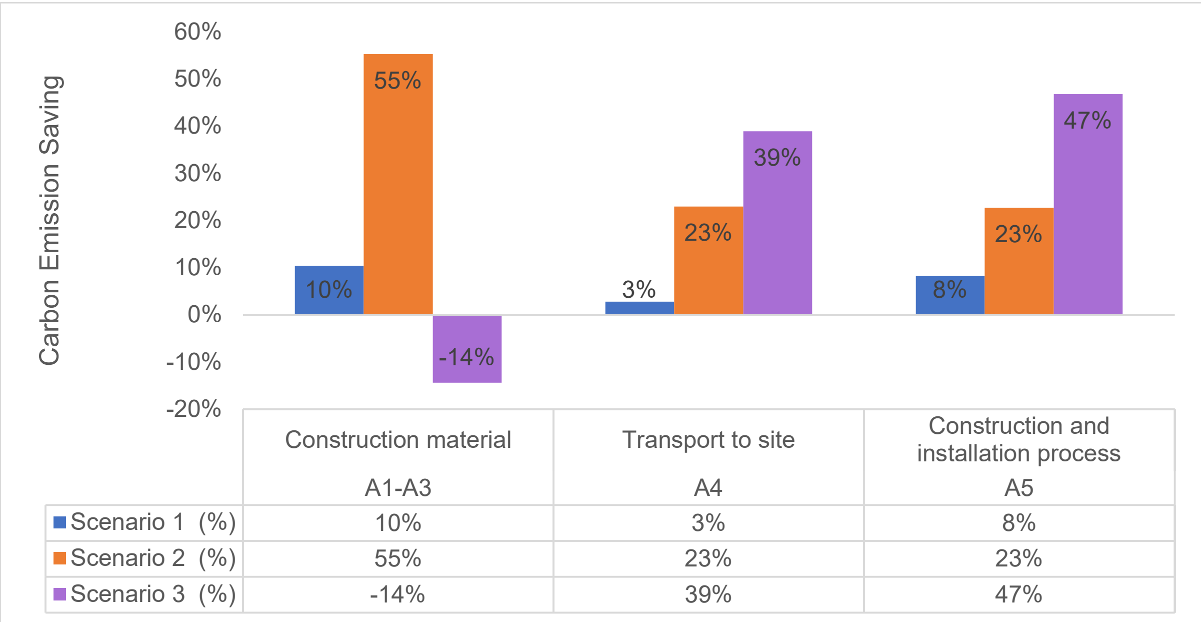


Figure 4.3: Upfront carbon emission savings against the base case

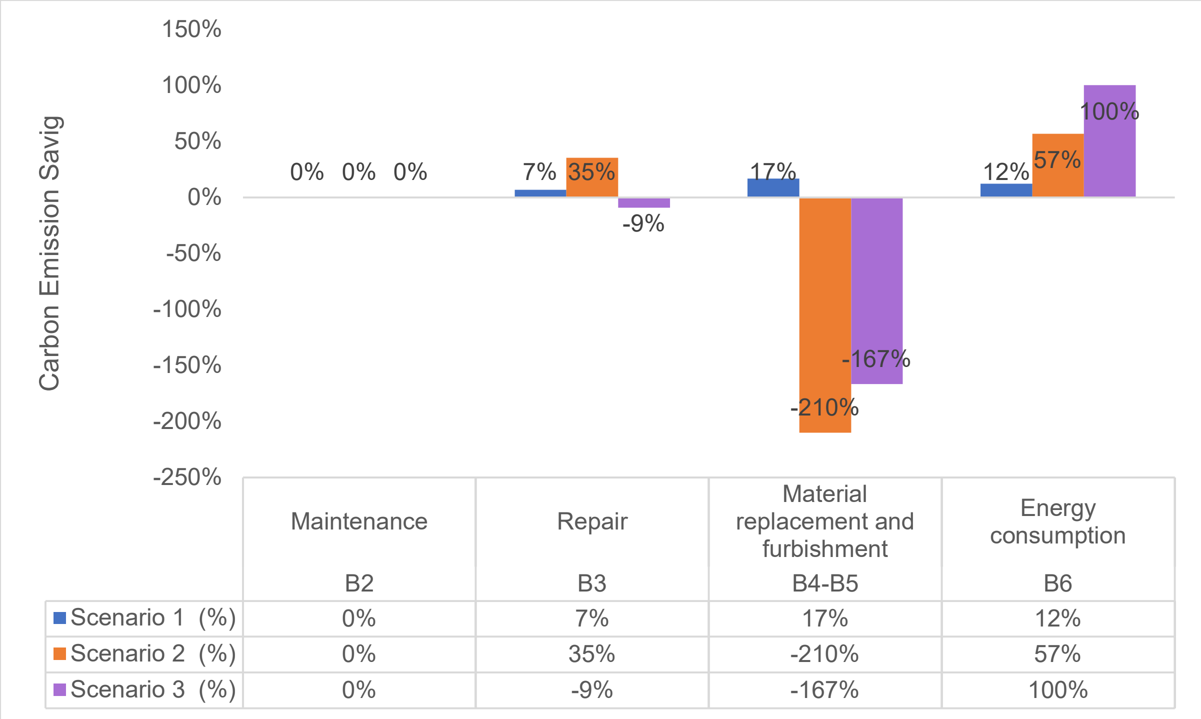
In the In-use phase, the base case constituted the largest carbon emission generation at 544,417kg CO_2e, with energy consumption accounting for 97% of this total. Moreover, the in-use carbon emissions are 37 times higher than the combined carbon emissions from modules A, C and D. This elevated emission generation was seen across all the cases, emphasising the importance of developing for in-use phase carbon emission reduction. Since the maintenance carbon emissions were calculated using the RICS kg CO_2e/m^2 gross internal area methodology, and all cases had the same typology, the carbon emissions were identical across the cases.

Scenario 1 achieved a 12% carbon emission reduction driven by the reduction in energy consumption. The 7% and 17% carbon emission reduction in the maintenance and repair module only constituted 1,371kg CO_2e savings, a negligible reduction. This indicates that the adoption of simple sustainable techniques, such as a thermal solar geysers and compact florescent bulbs will support operational carbon emission reduction as indicated by Participant 1.

Scenario 2 achieved a 53% carbon emission reduction, also driven by the reduction in energy consumption. However, the adoption of solar panels to produce 50% of the household's energy resulted in energy consumption dropping to 230,400kg CO_2e (57% reduction). This saving overshadowed the additional carbon emissions generated from material replacement and refurbishment compared to the base case, which constituted a 210% gain in emissions. The high material replacement emissions were due to solar panels only having an average life expectancy of 25 years.

Scenario 3 boasted the highest in-use carbon emission savings of 96%. The scenario's total energy consumption was covered by solar generated power, effectively reducing electricity consumption carbon emissions by 532,800kg CO_2e. Unlike scenario 2, where repairs, and material replacement and refurbishment were negligible, these items constituted the total carbon emissions for module B.

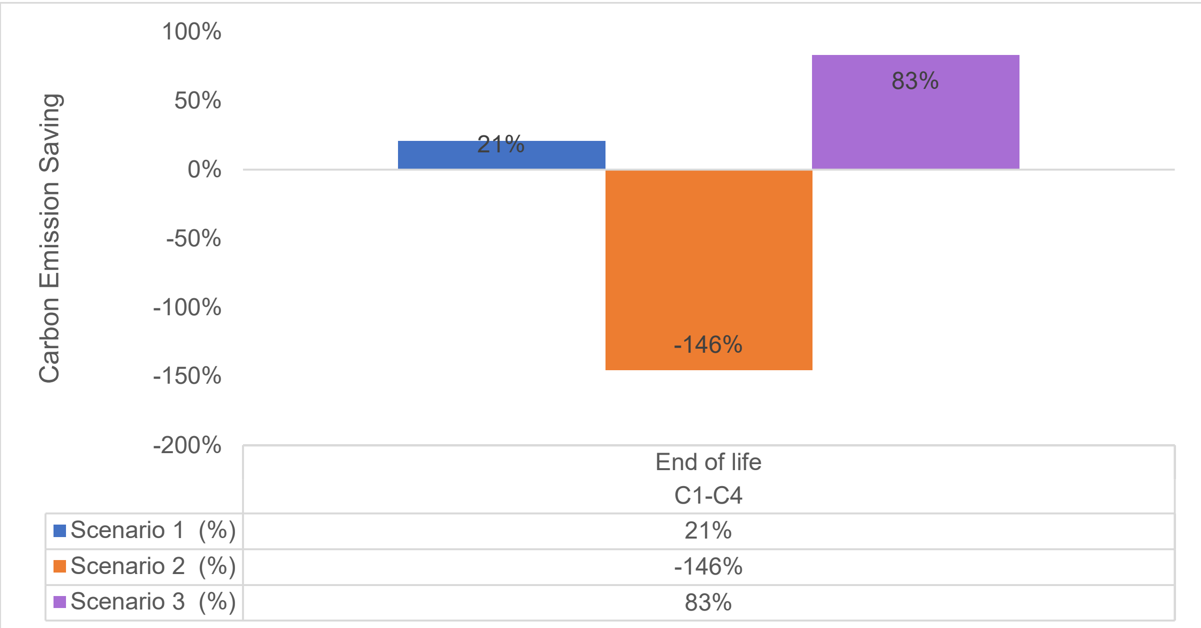
Notability, the carbon emissions generated using electricity constituted the highest carbon emissions, followed by replacements, and then repair. This indicates that fossil fuel generated electricity must be targeted for a house to aim for net-zero energy. Figure 4.4 illustrates the carbon emission percentage difference between the base case and the scenarios in-use phase.



	Maintenance B2	Repair B3	Material replacement and furbishment B4-B5	Energy consumption B6
Scenario 1 (%)	0%	7%	17%	12%
Scenario 2 (%)	0%	35%	-210%	57%
Scenario 3 (%)	0%	-9%	-167%	100%

Figure 4.4: In-use carbon emissions savings against the base case

The end-of-life carbon emissions, expressed in Figure 4.5, encapsulates demolition and waste processing, with the base case generating the highest carbon emissions at 3,906kg CO_2e. Scenarios 1 and 3 had 21% and 83% carbon emission reductions. Scenario 2's carbon emissions increased by 146%. The higher emissions were driven by the waste processing steps attributed to laminated timber and solar panels.



	End of life C1-C4
Scenario 1 (%)	21%
Scenario 2 (%)	-146%
Scenario 3 (%)	83%

Figure 4.5: End of life carbon emissions savings against the base case

Module D, information beyond construction works life cycle presented in Figure 4.6, encapsulates carbon emissions off-set by re-cycling materials. No scenario exported utilities and thus all off-set emissions are a function of internal impacts. Scenario 1 had the lowest carbon emission off-set. Scenarios 2 and 3 achieved 345% and 343% improved savings against the base case. These improved savings were driven by the re-use of solar panels, converting bricks and concrete to aggregate and the incineration of organic materials such as wood and hemp.

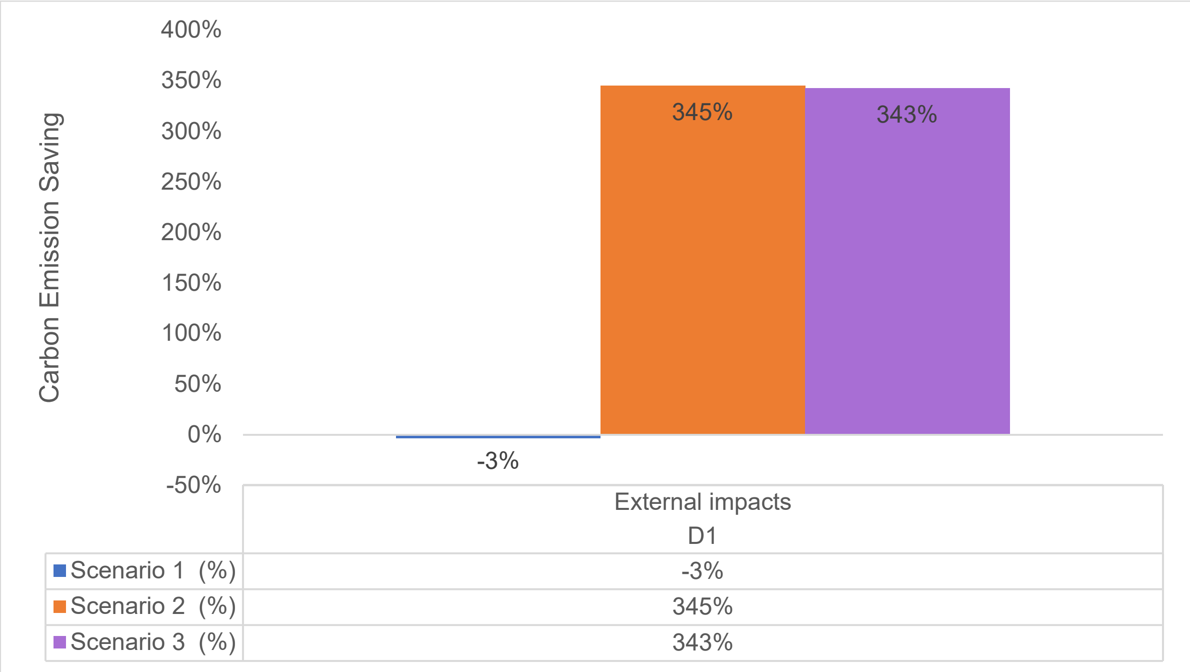
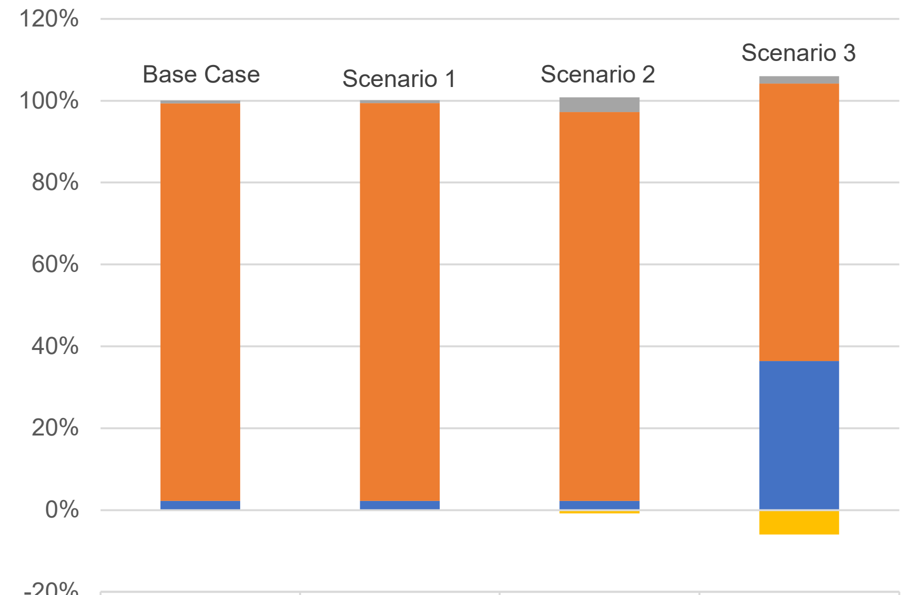


Figure 4.6: Information beyond construction works life cycle carbon emissions savings against the base case

An analysis of the modules indicates that Module B1-B6 is the predominant contributor to carbon emissions in the base case, accounting for 97% of the total emissions. This significant contribution diminishes the relative impact of the other modules, with Module A1-A5 responsible for only 2%, followed by Modules C1-C5 and D1-D2, whose contributions are minimal.

However, shifting the focus towards reducing the property's energy consumption through the installation of PV panels, demonstrated in Scenario 3, the carbon emissions form Module B1 - B6 decreased from 544,417kg CO_2e to 24,357kg CO_2e, marking a reduction of 520,060kg CO_2e. This reduction lowered the proportion of emissions from Module B1-B6 from 97% to 68%. Despite this marked decrease, Module B1-B6 remains the primary source of carbon emissions for Scenario 3, largely due to the need for solar panel replacements throughout the building's life cycle.

Furthermore, Module A1-A5 emerged as the second-largest contributor to total carbon emissions in Scenario 3, now constituting 36% of the overall emissions. This finding highlights the importance of utilising alternative, carbon-neutral building materials to further mitigate the building's carbon footprint. The variations in emissions across the different modules are depicted in Figure 4.7, underscoring the areas where developers and homeowners should focus their efforts to enhance sustainability and reduce environmental impact.



	Base Case	Scenario 1	Scenario 2	Scenario 3
D1-D2 Information beyond construction works life-cycle	0%	0%	-1%	-6%
C1-C4 End of Life	1%	1%	4%	2%
B1-B6 In-use	97%	97%	95%	68%
A1-A5 Upfront Carbon	2%	2%	2%	36%

Figure 4.7: Whole life cycle carbon emission module breakdown

4.4.3 Embodied V Operational Carbon Emission Analysis

The modelled embodied carbon emissions throughout the building's life cycle never reached zero in any scenario. However, Scenario 1 demonstrated a modest reduction in embodied carbon emissions, achieving a 12% reduction compared to the base case. In contrast, both Scenarios 2 and 3 achieved higher embodied carbon emissions than the base case, with increases of 48% and 32%, respectively. This increase is attributed to the use of solar panels, while reducing operational carbon, contributed to higher embodied emissions.

The results, as shown in Table 4.7, highlighting the complexities involved in reducing embodied carbon. Although Scenario 1 achieved some savings, Scenarios 2 and 3 exceeded the base case emissions due to trade-offs between operational efficiency and material selection. This illustrates the need for a balanced approach that considers both operational and embodied carbon when pursuing sustainable building designs.

Table 4.7: Embodied carbon emission savings

Embodied Carbon Emission Savings			
	Actual kg CO2e	kg CO2e Saving	Percentage
Base Case (kg CO2e)	27 291	0	0%
Scenario 1 (kg CO2e)	23 920	3 372	12%
Scenario 2 (kg CO2e)	40 319	-13 028	-48%
Scenario 3 (kg CO2e)	35 915	-8 624	-32%

Operational carbon emissions decreased as the sustainability level improved with each Scenario. Scenario 1 achieved the lowest energy savings of 12% compared to the base case, reflecting limited operational carbon emission reductions. In contrast, Scenario 2 resulted in a more substantial reduction of 57%, indicating a significant enhancement in energy performance. Scenario 3 achieved the highest level of sustainability, with a 100% reduction in operational carbon emissions, effectively reaching a net-zero operational carbon footprint.

This progression underscores the impact of integrating renewable energy solutions, such as solar panels, in achieving substantial reductions in operational carbon emissions. Scenario 3, which utilised solar panels to generate one hundred percent of the household's energy, exemplifies how adopting renewable energy sources can eliminate operational carbon emissions entirely.

The results are summarised in Table 4.8, which provides an overview of the operational carbon emission savings across the different scenarios.

Table 4.8: Operational carbon emission savings

Operational Carbon Emission Savings			
	Actual kg CO2e	kg CO2e Saving	Percentage
Base Case (kg CO2e)	532 800	0	0%
Scenario 1 (kg CO2e)	468 000	64 800	12%
Scenario 2 (kg CO2e)	230 400	302 400	57%
Scenario 3 (kg CO2e)	0	532 800	100%

As expressed earlier, operational carbon emissions significantly exceed embodied emissions, as illustrated in Table 4.9. In the Base Case, Scenario 1, and Scenario 2, operational emissions, far surpass embodied emissions. Scenario 1 implemented basic energy-saving measures which did not proportionally reduce operational emissions because embodied emissions remained at 5%. Scenario 2, which included PV panels covering 50% of energy needs, reduced operational emissions from 95% in the Base Case to 85%, representing a 10% reduction.

In contrast, Scenario 3, which employed PV panels to generate 100% of the building's energy, eliminated operational carbon emissions. This highlights the critical importance of sourcing 100% of operational energy from renewable sources to attain net-zero operational carbon emissions. The limited improvements seen in Scenarios 1 and 2 underscore the need for more comprehensive sustainability measures. This expresses the concern that partial approaches are inadequate to effectively address the predominance of operational carbon emissions.

Table 4.9: Embodied v operational carbon emissions

Embodied V Operational Carbon Emissions		
	Embodied	**Operational**
Base Case (kg CO2e)	5%	95%
Scenario 1 (kg CO2e)	5%	95%
Scenario 2 (kg CO2e)	15%	85%
Scenario 3 (kg CO2e)	100%	0%

4.4.4 Whole Life Cycle Cost Analysis

The whole life cycle cost analysis provides a high-level overview of the financial implications of the 3 Scenarios, incorporating the initial construction costs, operational costs, and demolition costs. This analysis will provide an economic overview of pursuing higher levels of sustainability in building designs.

The initial findings are summarised in Table 4.10, which presents the whole life cycle costs for the three ANZEH Scenarios. The Base Case was the least viable building approach, costing R2,265,150. This was followed by Scenario 1 at R1,949,737, Scenario 2 at R1,662,305, and Scenario 3 at R1,055,603.

Table 4.10: Whole life cycle cost of the modelled scenarios

Whole Life Cycle Cost For 3 Varying Levels of ANZEH					
Category		**Base Case**	**Scenario 1**	**Scenario 2**	**Scenario 3**
Construction Cost	Construction Cost	R553 120	R548 575	R669 593	R607 895
Variance (%)			**-1%**	21%	10%
Operational	Maintenance	R55 312	R54 858	R66 959	R60 790
	Replacement	R164 375	R153 178	R385 861	R449 502
	Energy consumption	R1 367 343	R1 219 077	R596 981	R0
Variance (%)			**-10%**	**-34%**	**-68%**
Demolition	Demolition & Recycling	R125 000	-R25 951	-R57 089	-R62 583
Variance (%)			**-121%**	**-146%**	**-150%**
Total		**R2 265 150**	**R1 949 737**	**R1 662 305**	**R1 055 603**
Variance (%)		**-**	**-14%**	**-27%**	**-53%**

Scenario 1 reflected the base case, utilising conventional building practices that resulted in modest 14% cost savings compared to the Base Case. However, Scenario 2, which incorporates PV panels to cover 50% of the energy needs, showed an increase in construction costs, 21% premium against the Base Case, due to the additional investment in the PV system and the added costs attributed to the cross-laminated timber. Despite the higher construction, maintenance, and replacement costs, Scenario 2 reduced whole life cycle costs by 27%. Scenario 3 achieved 100% renewable energy sourcing, resulting in the greatest long-term savings by eliminating electricity costs. This resulted in Scenario 3 reducing whole life cycle costs by 53% even though construction, maintenance, and replacement costs exceeded the Base Case.

While the initial investment for greater levels of sustainability are higher, as seen in Scenarios 2 and 3, the long-term benefits in terms of operational cost savings and environmental impact make the additional upfront investment viable. The whole life-cycle cost analysis underscores the importance of considering both initial and operational costs when making decisions around ANZEH, highlighting that sustainability measures can lead to financial benefits over the building's life span.

4.5 Discussion of the Findings

The findings from the study showcase a strong alignment with the observations in the literature review, particularly regarding the sustainability challenges and opportunities within the South African construction industry.

Affordability emerged as a multifaceted concept, with participants emphasising not only the cost of acquisition but also long-term operational expenses, including energy and maintenance costs which follows Ibrahimu *et al.'s* (2018) observations. This study highlighted the importance of considering the total cost of ownership, incorporating utility and operating costs rather than just the upfront purchaser price. This broader view aligns with the need for durable, low-maintenance housing that minimises long-term financial burdens on occupants (Gan and Hill, 2009; World Economic Forum, 2019). An insight that arose from the findings which wasn't discussed in the literature, was the role consumer perception. Participants expressed that consumers have an inclination for free-standing houses over apartments and households tend to prefer traditional building materials making the adoption of alternative cheaper or sustainable materials harder. This cultural and psychological inclination presents a significant barrier to the adoption of alternative, more affordable or sustainable materials. The resistance to non-traditional housing forms and materials suggests that affordability strategies must also address perceptions and preferences, not just economic or technical feasibility scenarios.

All participants agreed that a building's degree of sustainability is measured using a "green" rating tool (Griffiths *et al.*, 2020) because South Africa's building codes do not promote sustainable development. Both the findings and literature emphasized the inadequacies of South Africa's building codes which provide only minimal energy efficiency standards. Zuo and Zhao's (2014), and Moghayedi *et al.* (2022) highlighted similar issues, underscoring the lack of progressive legislation or policies that incentivise sustainable building practices. The findings also reflect this limitation, as participants pointed to the absence of embodied carbon guides and the complexities involved in measuring embodied carbon due to the diverse materials used in construction. Participants indicated that the preferred rating tool to use is Edge because it is less intricate and affordable in relation to comparable tools like the GBCSA Green Star tool. It was also highlighted that these tools are limited in grading the level of sustainability by their measures, which has resulted in an industry shift from calling them "green rating tools" to "resource efficiency tools". This observation gains significance when assessing ANZEH, as ANZEH solely concentrates on energy conservation, leaving out other vital sustainability aspects, like water.

The interviews revealed that South Africa's building codes do not focus on embodied carbon emissions with no formal embodied carbon guide. Moreover, the diverse nature of materials in the construction industry makes measuring embodied carbon a complex and intricate task. The limited embodied carbon information, expressed in the interviews, were also experienced within the modelling portion of the research. The qualitative embodied v operational analysis revealed that the use of conventional construction techniques and materials only reduced embodied carbon by a maximum of 12% (Scenario 1), substantiating the participants claims. While operational carbon is the main focus of SANS 10400-XA (2023), with a comparable energy saving of 12% (Scenario 1). Operation energy reductions achieved through conventional construction techniques using SANS 10400-XA was limited to 12%. This was due to the building code only providing minimal energy efficient standards, following Moghayedi *et al.* (2022) observation that South Africa's lack of sustainable building codes, legislation and policies has hindered the development of a sustainable built environment. The findings also add nuances to the literature by demonstrating how geographic and regulatory contexts, as highlighted by Lima et al. (2021), shape sustainability outcomes. In South Africa, where building codes like SANS 10400-XA offer only minimal energy efficiency standards, the potential for operational carbon reduction is limited unless supplemented by renewable energy systems. This contrasts with findings from regions with more stringent codes, where baseline performance is already higher. These observations and literature context underlines the significant legislative and building code policy changes that will be required to advance South Africa’s minimum sustainability requirements. However, the pros and cons of aggressive sustainability policies must be carefully weighed, as rapid changes could adversely affect smaller developers lacking the resources and skills to adapt.

Another noteworthy parallel lies in the reliance on renewable energy systems, especially solar panels, as a means to achieve substantial operational carbon reductions. The adoption of innovative construction techniques and materials exponentially improved the energy savings, with the adoption of solar panels reducing the largest portion of carbon emissions. Scenario 2, where solar panels supplied 50% of the household’s energy need, reduced operational energy by 50%. Scenario 3, achieved a 94% carbon reduction by generating 100% of its operational energy demand, demonstrating the role of renewable energy in approaching an ANZEH. However, none of the scenarios fully achieved net-zero energy, with only Scenario 3 coming close. This underscores a key insight for an ANZEH to be realized, and that the total annual energy consumption must be offset entirely by clean, renewable generation through decentralised systems like solar PV. This requirement is especially important in South Africa’s high-carbon grid context, where grid-supplied electricity undermines energy neutrality.

These findings highlight that while passive design and efficient materials contribute meaningfully to energy reduction, achieving true net-zero energy hinges on the full integration of renewable energy systems. Moreover, the success of Scenario 3 illustrates that ANZEH is technically feasible, but its widespread adoption will depend on addressing cost, policy, and infrastructure barriers to renewable energy deployment.

The material selection has an influence on embodied carbon and overall sustainability outcomes. Upfront embodied emissions (Modules A1–A5) were primarily driven by material production and construction. Scenario 2 achieved the greatest embodied carbon reduction (51% lower than the base case) using laminated timber and a monologic roof system, which offered both lightweight efficiency and biogenic carbon sequestration. In contrast, Scenario 3, despite employing low-carbon materials such as autoclaved aerated concrete and hemp cladding, exceeded the base case's embodied carbon due to the inclusion of a solar PV system. Additionally, the use of lightweight, renewable, and locally sourced materials (e.g., laminated timber and hemp cladding) reduced transport and construction emissions, highlighting the role of logistics and material density in upfront carbon performance. Scenarios incorporating recyclable or reusable materials also achieved notable offsets in Module D, demonstrating the value of modular design and circular economy strategies. Although maintenance-related modules (B2–B5) contributed minimally, the durability and replacement cycles of key components, like solar systems, proved more impactful over time.

Understanding the NZEB critical characteristics that promote the development of ANZEH will help a developer and household to implement and measure their sustainability impact. The role of passive design strategies was another shared theme between the literature and findings. Participants stressed the importance of incorporating design elements such as orientation, glazing, insulation, and roof reflectivity to optimize energy efficiency, which echoes insights from the literature (Pacheco *et al.*, 2012; Fantucci and Serra, 2019; Wang *et al.*, 2021). The need to optimise space allocation, embrace energy-efficient designs, and building orientation were cited by the participants as crucial design concepts. The use of software will improve these designs and allow developers or households to identify operational and embodied carbon emission trends before construction takes place.

Participants discussed both the opportunities and challenges of integrating sustainability into affordable housing. These observations align with the literature on the variability of carbon emissions across building types and contexts. As Tejero et al. (2018) and Minunno et al. (2021) explained that the carbon footprint and energy profile of a building is influenced by several interrelated factors, including building type, intended use, material selection, construction methods, geographic context, and occupant behaviour. These variables create significant differences in both embodied and operational emissions, necessitating a context-specific approach to sustainable construction. This complexity is reflected in the participants' feedback, where the integration of sustainability into affordable housing was seen as both an opportunity and a challenge. While the long-term benefits of net-zero energy designs were widely acknowledged, high upfront costs, particularly for technologies like solar panels or alternative building materials were identified as barriers to entry. Despite these challenges, participants noted that these initiatives could lead to substantial reductions in operational costs and emissions over the long-term. These observations are supported by the whole life cycle cost analysis which showed that improving the sustainability of a home can result in up to 53% financial savings. This reinforces the literature's observation for a "total cost of ownership perspective". This approach considers not just initial capital outlay but also long-term operational savings which is an essential consideration in affordable housing contexts where utility costs can undermine affordability over time.

The four ANZEH dimensions (Technical, social, environmental, and economic dimensions) discussed in the literature helped serve as a guiding framework for the critical success factors needed to transform a CAH into an ANZEH, and these findings reflect and extend these dimensions through both the participant insights and scenario modelling. The technical dimension, which includes passive design, building orientation, and material selection (Biyik et al., 2017; Chen et al., 2017), was evident in the participants' emphasis on orientation, glazing, insulation, and roof reflectivity. Scenario 2 achieved the greatest embodied carbon reduction using laminated timber and a monologic roof system if you exclude the additional of the PV system, validating the literature's emphasis on lightweight, modular, and biogenic materials (Cortesão et al., 2023). The social dimension, which focuses on occupant behaviour and environmental awareness (Never et al., 2022), was reflected in the cultural resistance to non-traditional housing forms and materials, a barrier not widely discussed in existing literature, highlighting the need for psychological and structural strategies (Steg, 2008) to shift perceptions. The environmental dimension, centred on renewable energy and low-carbon materials (Wells et al., 2018; Wu and Skye, 2021), was reinforced by Scenario 3's 94% operational carbon reduction through solar PV, though it also revealed the trade-off with increased embodied carbon. The economic dimension, which emphasised energy-efficient technologies and financial incentives (Deng et al., 2014), was evident in participants' concerns about high upfront costs and the limited accessibility of green bonds, despite whole life cycle cost analysis showing up to 53% savings, reinforcing the need for a total cost of ownership perspective. These findings not only validate the literature but also contribute new insights, such as the role of consumer perception, the embodied-operational carbon trade-off, and the need for inclusive financial tools, offering a comprehensive, context-specific understanding of how ANZEH principles can be implemented in South Africa's affordable housing sector.

The use of conventional building techniques such as using prefab, or the use of conventional lighter building materials will reduce building times and material costs without high upfront costs. While, strategies to reduce heating, lighting and cooking costs will target high housing energy consumers during a building's lifespan, supporting Cheung (2017) and Tsioumas (2018) observations. The installation of LEDs and water flow rate restrictors are non-cost evasive items that help curb the energy consumption of geysers and lights. The introduction of green bonds will enhance the viability of ANZEH. However, these bonds, which offer lower interest rates, primarily target large developers, leaving homeowners and small developers without significant benefits. Policymakers and financial institutions engaged in affordable housing initiatives should leverage sustainability index tools that encompass all spheres of stakeholders (Moghayedi and Awuzie, 2023). By doing so, they can encourage designers and developers of affordable housing projects to adopt more sustainable building practices regardless of project scope or size. Consequently, the integration of advanced sustainable technologies and techniques will be required to achieve ANZEH, their long-term operational cost reductions must be weighed against their high initial capital to overcome barriers to entry.

ANZEH falls within the scope of sustainable innovative affordable housing, emphasising the necessity for novel construction methods and materials to address housing deficits in developing regions, particularly Southern Africa (Moghayedi and Awuzie, 2023; Moghayedi *et al.*, 2023; Moghayedi *et al.*, 2024). Similarly, Moghayedi *et al.* (2023) explores various sustainable design techniques, materials, and technologies suitable for the South African climate. Their research demonstrates significant reductions in energy consumption using passive designs and the generation of on-site renewable energy, validating the effectiveness of ANZEH techniques. Further, the need for alternative construction approaches presented in the ANZEH modelling to reduce embodied and operational carbon emissions is fundamental to overcoming the shortfalls of conventional building practices. This observation is supported by Moghayedi and Awuzie (2023) findings that traditional construction methods in affordable housing projects fail to tackle sustainability-related issues in Southern Africa. It is evident that stakeholders need to measure their level of sustainability to ascertain their building's whole life cycle impact. Additionally, a study by Moghayedi *et al.* (2022) titled *Appraising the nexus between influencers and sustainability-oriented innovation adoption in affordable housing projects* identified the internal and external factors influencing the adoption of innovative sustainability techniques. It highlights challenges such as high costs, lack of technical knowledge, and regulatory barriers that impede the widespread adoption of such techniques in affordable housing. It was evident from the interviews that the professionals face similar challenges and industry wide strides will be required to synergise these spheres. Furthermore, Moghayedi *et al*. (2024) underscores the correlation between the limitations of conventional construction methods in addressing Africa's housing crisis and the potential of innovative practices, such as 3D printing, as pioneering solutions. By quantifying the advantages of these alternative approaches, stakeholders will have the foundation to make educated decisions when adopting and implementing sustainably orientated innovations.

The environmental impact of ANZEH was clearly expressed by the participants and within the quantitative model. Additionally, the interconnectedness of financial and environmental impacts, wherein installing energy-efficient fittings to diminish energy consumption resulted in decreased operational CO_2 emissions and reduced energy procurement needs. The adoption of simple conventional construction techniques, such as the use of precast slabs, hollow bricks and using re-cycled demolition material marginally decreased embodied carbon emissions. This approach was modelled within Scenario 1 which resulted in a 12% embodied carbon emission reduction, indicating that developers do not have to adopt innovative construction techniques or materials to reduce embodied emissions. While Scenarios 2 and 3 exhibit higher embodied emissions, with increases of 48% and 32%, respectively. These increases stem from the materials and technologies used, such as solar panels, which, while lowering operational emissions, raised embodied carbon due to their material demands and replacement needs throughout the building's life cycle. The integration of renewable energy, solar panels, significantly reduced operational carbon emissions with PV solar generation being the widely adopted renewable energy generation method.

In contrast, operational carbon emissions decrease progressively across all scenarios. Scenario 1 achieved a modest 12% reduction, while Scenario 2, which incorporates PV panels covering 50% of energy consumption, delivered a 57% reduction. Scenario 3, which relied entirely on solar energy, eliminated operational carbon emissions, demonstrating the significant impact that renewable energy technologies will have on reducing operational emissions. The qualitative analysis also confirmed the necessity of renewable energy, particularly solar panels, to achieve net-zero operational carbon emissions. This input was reflected in the modelled scenarios, where PV panels were integral at reducing operational carbon, supporting Kumar's (2020) findings. This alignment between qualitative feedback and quantitative modelling emphasised the need to adopt renewable energy sources.

This underscores the trade-off between operational energy savings and the additional embodied carbon from incorporating advanced technologies. While Scenario 3 effectively eliminates operational carbon, embodied carbon remained a critical issue. Developers must focus on both operational and embodied emissions, particularly by using sustainable materials, to minimise the overall carbon footprint of ANZEH. The continued reliance on conventional materials in Scenario 1 provides a more affordable pathway to reducing emissions but highlights the limited potential for significant carbon reductions without renewable energy technologies. Renewable energy technologies, especially solar panels, play a crucial role in reducing operational carbon emissions. Therefore, a balanced approach is necessary to minimise both embodied and operational carbon emissions, emphasising the need for renewable energy while managing material impacts. However, to achieve a true net-zero energy house, innovation in both materials and construction techniques is essential to address embodied carbon.

4.6 Summary of the Chapter

This chapter presented and discussed the qualitative and quantitative findings. The qualitative analysis revealed insights into the sustainability techniques and practices adopted by industry professionals to deliver sustainable housing designs. The key techniques and materials emanating from the interviews were used to guide the modelling of varying levels of ANZEHs. The modelling sought to assess the effectiveness of different approaches in reducing embodied and operational carbon emissions by employing different construction techniques and building materials. By addressing both qualitative and quantitative aspects, the study provides a holistic understanding of ANZEH's life cycle carbon impacts and offers pathways to making sustainable, affordable housing a reality.

The following chapter will draw conclusions based on the findings to address the research aim, and objectives. The chapter will further outline the research’s contribution to knowledge, recommendations and avenues for further research.

5 CONCLUSION

5.1 Introduction

This chapter will offer an overview of the research objectives, research questions, and research aims, as well as an assessment of their attainment. Subsequently, it will present the research proposition outlined in Chapter 1. Finally, the chapter will conclude with recommendations.

5.2 Revisiting Research Questions, Aim, and Objectives

The research aim was stated in Chapter 1 as:

This study aims to evaluate the impact of affordable net-zero energy house on the environmental life cycle sustainability of affordable housing in South Africa.

The research aim was achieved through the literature review, interviews and quantitative modelling. The primary research question was:

What impact will an affordable net-zero energy house have on life cycle sustainability of affordable housing in South Africa?

This question was achieved with the quantitative analysis in Chapter 4.3 revealing that carbon emissions can be reduced by up to 94% within the South African context. It was further revealed in the findings that increasing the number and level of sustainable initiatives will enhance the life cycle impact of ANZEH. The adoption of solar installations and move towards 100% renewable operational energy had the largest impact on reducing carbon emissions. However, the cost component of ANZEH and the skill set of South Africa's built environment industry was identified as a limiting factor. Therefore, the adoption and integration of ANZEH will reduce a building's life cycle emissions, but as sustainability sentiments evolve and ANZEH becomes more common, the ANZEH space will build traction and drive a new wave of housing development in the country.

To further address the primary research question, the following secondary research questions and corresponding research objectives were evaluated:

Research Question 1: *What are the critical success factor mechanisms that underpin an affordable net-zero energy house?*
Objective 1: *Identify and analyse the critical success factor mechanisms that form the foundation of an affordable net-zero energy house.*

This was achieved by performing a literature review and quantitative analysis. The literature revealed that 4 ANZEH dimensions, namely technical, social, environment, and economic dimensions underpin the critical characteristics of ANZEH. Table 4.2 in Chapter 4.2 summarised the attributes and characteristics identified from the interviews that defined an ANZEH. These findings guided the quantitative modelling, which provided an LCCE analysis of three varying levels of ANZEHs. The analysis indicated which building elements and techniques were most effective in reducing carbon emissions. This multi-faceted approach allowed for a holistic understanding of the necessary factors impacting ANZEHs.

Research Question 2: *What are the construction, material, technology and building technique factors that must be considered in achieving affordable net-zero energy house?*
Objective 2: *Determine the construction, material, technology and building technique factors that must be considered in achieving affordable net-zero energy houses.*

These factors were highlighted in the literature review and identified through the interviews, which were used to guide the modelling process. It was further noted that South Africans prefer conventional building techniques favouring brick and motor homes. By a similar token, South Africa's construction industry has only adopted sustainability building techniques and materials in partial aspects, favouring conventionally sustainability approaches. Further, the integration of innovative building materials, like hemp cladding, aerated concrete and solar panels must be utilised to achieve an ANZEH.

Research Question 3: *What impact will affordable net-zero energy house have on reducing South Africa's life cycle emissions?*
Objective 3: *Evaluate the state and potential influence of the affordable net-zero energy houses on South Africa's life cycle emissions.*

South Africa's building regulations do not elude themselves to aggressive sustainability measures, but rather rudimental sustainability requirements. SANS 10400-XA focuses on the minimal required energy efficiency of real estate. It was noted that South Africa's building standards do not provide any guidance on embodied energy. Therefore, the drive towards ANZEH will educate industry professionals on aggressive embodied and operational carbon reduction methods and techniques and open the market to a new sustainability driven demand. This study demonstrates that ANZEHs can drastically reduce both embodied and operational emissions, offering a more aggressive and effective response to climate change than current standards. By shifting industry practices and building consumer demand, ANZEHs could lead to transformative reductions in the built environment's environmental impact and align housing development with long-term sustainability goals.

Objective 4: *Evaluate the economic life cycle performance of an affordable net-zero energy house in South Africa.*

The whole life cycle cost analysis demonstrated significant cost savings over the lifespan of an ANZEH. Although the initial construction costs were higher due to the integration of innovative building materials and sustainable construction techniques, these costs were offset by substantial operational savings post-construction. Moreover, the adoption of green financing options could reduce the initial investment required for ANZEH projects, thereby lowering the barrier to entry and facilitating wider adoption. Green financing includes incentives such as lower interest rates, grants, and subsidies for sustainable building practices, which can make ANZEHs more accessible and attractive to developers and homeowners alike. The findings validate the objective and ANZEHs can enhance the economic sustainability of the residential sector in South Africa, making them a viable and attractive option for future housing developments.

5.3 Significance of the Research

Despite the overwhelming evidence in support of ANZEHs stated earlier, many developers have been opposed to embrace sustainability techniques, materials and methods in their housing projects due to their limited understanding and the pursuit of lower building costs. For this reason, it is vital to understand how to accelerate the implementation of ANZEHs and their impact on the sustainability life cycle. This research will provide the resources to guide and evaluate the holistic nature of ANZEHs for developers and policy makers. This research will boost the sustainability mindset of affordable housing from the design phase through to the operational phase, ultimately improving the sustainability and dignified nature of affordable housing.

Consequently, this dissertation contributes to the development of ANZEHs research and bridges the educational gap between ANZEHs, developers, policy makers, and the end user by providing a novel approach to the achievement of ANZEHs. This dissertation will guide property developers and policy makers towards cost-effective, environmentally friendly, and economically viable housing for low-income households. Therefore, this dissertation will facilitate developers and policy makers in the decision-making and implementation stage of ANZEHs that will enhance the sustainability of the urban environment and promote the economic prosperity of households.

5.4 Conclusion

The findings of this study have provided significant insights into the energy and environmental sustainability implications of ANZEH in South Africa. The findings clearly demonstrate that the implementation of ANZEH enhances the environmental and economic sustainability within the residential built environment.

There's a critical need for affordable housing in South Africa, driven by rapid urbanisation, housing shortages, and economic challenges. Affordable housing is intended for individuals who cannot afford market-related prices or do not meet the criteria for social housing. Accordingly, this dissertation defines affordability as households spending no more than 30% of their income on gross housing expenses. At the same time, the built environment has also been identified as a major contributor to negative environmental impacts, particularly through embodied and operational carbon emissions.

Energy consumption, particularly from fossil fuel-based grids like South Africa's, is a primary driver of operational carbon emissions. Therefore, reducing energy demand through passive design and meeting energy needs with clean, renewable sources not only achieves energy neutrality but also significantly lowers operational carbon output. However, the relationship between embodied and operational energy is not linear. Technologies that enable net-zero energy, such as solar panels, carry embodied carbon costs due to their manufacturing and replacement cycles. This introduces a trade-off that while operational energy is minimised, embodied emissions may rise. Further, as operational energy use decreases through efficiency and renewable energy, the embodied energy and its associated carbon footprint become proportionally more significant.

Although none of the scenarios examined in this study achieved complete net-zero energy emissions, Scenario 3 approximated this goal with a 94% reduction in carbon emissions. These results highlight the substantial progress ANZEH can make towards addressing the environmental crisis and the housing challenges in South Africa. The qualitative analysis revealed that the adoption of ANZEHs is influenced by various factors, including the availability of sustainable building materials, the level of awareness and knowledge among stakeholders and homeowners, and the financial viability of sustainable housing projects. The literature corroborates these findings, indicating that the successful implementation of ANZEHs requires a holistic approach that considers technical, social, environmental, and economic dimensions. The significance of these findings lies in their potential to drive a paradigm shift towards more sustainable and energy-efficient practices in the development of affordable housing.

One of the key challenges identified in the study is the high upfront cost of sustainable building materials and technologies. This challenge is consistent with the literature, which highlights the need for financial incentives and support mechanisms to promote the adoption of sustainable housing practices. The study suggests that green financing options, such as green bonds and sustainability-linked loans, can play a crucial role in addressing this challenge and making the initial ANZEH cost more financially viable.

Furthermore, this research underscores the importance of considering the specific needs and challenges faced by low-income housing groups in South Africa. While the country has established green residential rating systems to promote net-zero carbon buildings, these systems do not adequately address the economic constraints, social circumstances, and environmental aspirations of low-income communities. Compounding this, is the preferential use of conventional building materials by this income group over sustainable options. There's a need for increased awareness of the benefits of sustainable materials to reduce carbon emissions and improve long-term operating costs.

Additionally, there is a need for skills transfer and the integration of sustainable technologies into local communities and construction companies. By fostering small business specialisations and increasing ANZEH awareness, skill development can be enhanced. Governmental policies must also establish a foundation for robust sustainability frameworks during the planning, construction, operational, and end-of-life phases of low-income housing projects. Such frameworks provide clarity and consistency, reduces uncertainty and facilitates long-term planning for developers. This, in turn, will stimulate investment in ANZEH practices, driving down costs and enhancing competitiveness within the sustainability landscape of the built environment. By addressing the economic limitations, social considerations, and environmental objectives of low-income communities, the apprehension and implementation of ANZEH will improve. This holistic approach will increase the supply of ANZEH in South Africa, providing a sustainable and affordable housing solution that aligns with the diverse needs of the population while contributing to a more environmentally friendly built environment.

In summary, this dissertation provides a foundational understanding of the significant benefits and challenges associated with the implementation of ANZEH in South Africa. By addressing both environmental and economic perspectives, the research offers a holistic approach to evaluating ANZEH models, thereby equipping homeowners, developers, and policymakers with the knowledge necessary to make informed decisions. Ultimately, the adoption of ANZEH has the potential to transform the residential built environment, fostering a more sustainable nation.

5.5 Contribution to Knowledge

ANZEHs have remained relatively unexplored within the South African context, especially noting the lack of ANZEHs adoption. South Africa does have established green residential rating systems that aim to promote the creation of net-zero carbon buildings. However, it is worth noting that these existing systems do not adequately cater to the specific needs and challenges faced by low-income housing groups.

As a result, there is a pressing need for a more comprehensive understanding of ANZEHs that considers not only the economic constraints of low-income individuals and families but also their social circumstances and environmental aspirations. This holistic perspective is crucial for overcoming the barriers to ANZEH adoption in South Africa.

By addressing the economic limitations, social considerations, and environmental objectives of low-income communities, the apprehension and implementation of ANZEHs will improve. Such an approach will increase the supply of ANZEHs in South Africa, offering a sustainable and affordable housing solution that aligns with the diverse needs of the population while also contributing to a more environmentally friendly built environment.

Theoretically, the research provides a deeper understanding of sustainable housing practices and their environmental impacts, particularly within the South African context. It highlights the importance of integrating life cycle carbon assessments and advanced building modelling techniques into the planning and construction phases of affordable housing projects. This addition to the literature emphasises the need for a holistic approach that encompasses technical, social, environmental, and economic dimensions to effectively implement ANZEHs. Practically, the study underscores the necessity of financial incentives and support mechanisms, such as green financing options, to overcome the high upfront costs associated with sustainable building materials and technologies. The study also recommends educational programs and workshops to bridge the knowledge gap among developers and homeowners, demonstrating the long-term benefits of ANZEHs. By fostering government policies that establish robust sustainability frameworks and encouraging skill transfer within local communities, the implementation of ANZEHs can be significantly enhanced, leading to a more sustainable and affordable housing solution that aligns with the diverse needs of South Africa's economy.

5.6 Recommendations

The interviews revealed a persistent financial challenge in developing sustainable homes, along with unique approaches taken to balance costs and sustainability. The qualitative analysis provided an estimated carbon emission savings for various levels of sustainability adoption, showing that a focus on mitigating operational emissions will yield the largest carbon emission savings. Therefore, if a developer has a tight budget, a focus on renewable energy should be prioritised. Furthermore, the whole life cycle cost analysis revealed that, in the long term, the savings on electricity costs will exceed the initial investment.

Life cycle carbon assessment should be integrated into the planning stage to evaluate the total carbon emission of a building over its expected life. Premium development techniques such as building modelling should be adopted into affordable housing designs. This will provide a visualisation and analysis of building components, helping to optimise both design and construction processes before physical construction takes place. By adopting these advanced techniques, affordable housing developers can create more efficient, sustainable, and cost-effective housing solutions that meet the diverse needs of homeowners while also contributing to a sustainable built environment.

There is a need to address the existing gap in knowledge and awareness among both developers and potential homeowners regarding the long-term benefits of ANZEHs.

Educational programs and workshops can play a crucial role in this regard, highlighting the environmental and economic advantages of sustainable housing. Implementing demonstration projects and real-world case studies can further illustrate the tangible benefits and feasibility of ANZEHs, thereby encouraging broader adoption.

Acknowledging that the assessment of a housing project's environmental impact is voluntary beyond SANS10400-XA, there is a need for greater regulatory interventions. South African policy makers should design and phase in more aggressive sustainability building regulations. These policies should seek to help subsidise alternative sustainable techniques and technologies for low-income developments improving their feasibility amongst developers. Moreover, there is a need for skill transfer and the integration of sustainability technologies into local communities, fostering small businesses specialisations to increase ANZEH awareness and skill development. Lastly, governmental policies must propagate a foundation for robust sustainability frameworks during the planning, construction, operational and end of life phase of low-income housing projects. Robust regulatory frameworks provide clarity and consistency, reducing uncertainty and facilitating long-term planning for developers. This, in turn, will stimulate investment in ANZEH practices, driving down costs and enhancing competitiveness in the sustainability space of the built environment landscape.

5.7 Recommended Further Research

The scope of this thesis examined the residential housing sector, specifically aimed at assessing the life cycle sustainability of ANZEHs in South Africa. It is important to acknowledge that the researcher's focus is on the life cycle of carbon and did not encompass an in-depth analysis of social sustainability aspects and building costs. The study's scope is confined exclusively to residential buildings within the confines of South Africa and their embodied and operation energy consumption requirements. The prevalence of ANZEHs in the South African remains low and resulted in limited available knowledge and resources pertaining to ANZEHs within the context of South Africa, thereby influencing the extent and depth of the research findings.

This study's modelling was conducted for a single climatic zone within South Africa. While this approach allowed for a focused analysis, it limits the generalisability of the findings. South Africa encompasses a diverse range of climatic zones, each with distinct thermal performance requirements that influence building characteristics.

These variations affect both embodied and operational carbon emissions. As a result, the conclusions drawn from this study may not fully represent the performance of ANZEHs in other regions. Future research should consider simulating ANZEH design across multiple climatic zones to evaluate how regional differences impact carbon performance and cost-effectiveness.

The three modelled scenarios were simulated using data from OneClick LCA which will inherently have some degree of variability in terms of the modelled CO_2e emissions. Consequently, the findings from these simulations should be considered indicative rather than definitive, serving as a preliminary analysis. It is recommended that further research be conducted, particularly through case studies, to gain a nuanced understanding of the CO_2e emissions associated with the construction and operation of an ANZEH. This extended research should not be limited to the energy and environmental sustainability impact alone but should also evaluate the financial dimensions of ANZEH projects. A financial analysis will ascertain the economic feasibility and potential cost-benefit implications of implementing ANZEHs on a broader scale.

References

2Zero50 (2025) *Eskom's approved tariff restructuring: What does it mean for the consumer* [Online]. Available: https://www.2zero50.com/eskoms-approved-tariff-restructuring-what-does-it-mean-for-the-consumer/ [Accessed May 28, 2025].

Abelson, P. (2009) Affordable housing: concepts and policies. *Economic Papers: A journal of applied economics and policy*, **28**(1), 27-38.

Abson, D.J., Fischer, J., Leventon, J., Newig, J., Schomerus, T., Vilsmaier, U., von Wehrden, H., Abernethy, P., Ives, C.D., Jager, N.W. and Lang, D.J. (2017) Leverage points for sustainability transformation. *Ambio*, **46**(1), 30-39.

Acosta, I., Campano, M.Á. and Molina, J.F. (2016) Window design in architecture: Analysis of energy savings for lighting and visual comfort in residential spaces. *Applied Energy*, **168**(April), 493-506.

Adabre, M.A. and Chan, A.P.C. (2019) Critical success factors (CSFs) for sustainable affordable housing. *Building and Environment*, **156**(June), 203-214.

Ade, R. and Rehm, M. (2020) The unwritten history of green building rating tools: A personal view from some of the 'founding fathers'. *Building Research & Information*, **48**(1), 1-17.

Adema, W. and Plouin, M. (2021) *Building for a better tomorrow: Policies to make housing more affordable. OECD Employment, Labour and Social Affairs Policy Briefs*. Paris, France: OECD.

Aflaki, A., Mahyuddin, N., Mahmoud, Z.A.-C. and Baharum, M.R. (2015) A review on natural ventilation applications through building façade components and ventilation openings in tropical climates. *Energy and Buildings*, **101**(August), 153-162.

Africa, S.S. (2022) *South Africa's outh continues to bear the burden of unemployment* [Online]. Available: https://www.statssa.gov.za/?p=15407 [Accessed February 20, 2023].

Aguilar-Santana, J.L., Jarimi, H., Velasco-Carrasco, M. and Riffat, S. (2020) Review on window-glazing technologies and future prospects. *International Journal of Low-Carbon Technologies*, **15**(1), 112-120.

Ahmadi, A.M., Sabori, N.R. and Halim, M. (2020) A typical design for energy-efficient building: A case study of zero energy building. *Repa Proceeding Series*, **1**(1), 22-31.

Akbarnezhad, A. and Xiao, J. (2017) Estimation and minimization of embodied carbon of buildings: A review. *Buildings*, **7**(5), 1-24.

Akpan, E.C. (2022) Social Science Research and Philosophical Alignments. *Social Science Research*, **6**(9), 93-99.

Akpolat, A.G. and Bakirtas, T. (2018) The relationship between energy consumption, urbanization, and economic growth in new emerging-market countries. *Energy*, **147**(March), 110-121.

Aksoy, U.T. and Inalli, M. (2006) Impacts of some building passive design parameters on heating demand for a cold region. *Building and Environment*, **41**(12), 1742-1754.

Albatayneh, A., Mohaidat, S., Alkhazali, A., Dalalah, Z. and Bdour, M. (2018) The influence of building's orientation on the overall thermal performance. *International Journal of Environmental Science & Sustainable Development*, **3**(1), 63-69.

Alexander, M. (2023) *South Africa is a climate patchwork of warm coastal subtropics, hot deserts, humid highlands, snow-topped mountains and an enclave of*

Mediterranean weather in the southwest [Online]. Available: https://southafrica-info.com/land/south-africa-weather-climate/ [Accessed 15 March, 2023].
Alharthi, K. and Rehman, A.A. (2016) An introduction to research paradigms. *International Journal of Educational Investigations*, **3**(8), 51-59.
Alhorr, Y. and Elsarrag, E. (2013) Green building practices: Optimisation of CCHP and biomass heating for maximum CO2 reduction in a mixed-use development. *International Journal of Sustainable Built Environment*, **2**(1), 99-108.
Almalki, S. (2016) Integrating Quantitative and Qualitative Data in Mixed Methods Research--Challenges and Benefits. *Journal of education and learning*, **5**(3), 288-296.
Amaratunga, D., Baldry, D., Sarshar, M. and Newton, R. (2002) Quantitative and qualitative research in the built environment: application of “mixed” research approach. *Work study*, **51**(1), 17-31.
Anacker, K.B. (2019) Introduction: Housing affordability and affordable housing. In: Taylor & Francis, 1-16.
Ancell, S. and Thompson-Fawcett, M. (2008) The social sustainability of medium density housing: A conceptual model and Christchurch case study. *Housing Studies*, **23**(3), 423-442.
Andrews, T.C. and Reinholz, D.L. (2020) Change theory and theory of change: what’s the difference anyway? *International Journal of STEM Education*, **7**(1), 2.
Andriukaitene, R., Vveinhardt, J. and Zukauskas, P. (2018) Philosophy and paradigm of scientific research, *Management culture and corporate social responsibility*, pp. 121-138. London, United Kingdom: Intechopen Limited.
Anser, M.K., Alharthi, M., Aziz, B. and Wasim, S. (2020) Impact of urbanization, economic growth, and population size on residential carbon emissions in the SAARC countries. *Clean Technologies and Environmental Policy*, **22**(4), 923-936.
Anser, M.K., Chen, Z., Peng, M.Y.-P. and Wang, Z. (2023) Research on the impact of green finance and renewable energy on energy efficiency: The case study E−7 economies. *Renewable Energy*, **205**(March), 166-173.
Arens, E., Federspiel, C.C., Wang, D. and Huizenga, C. (2005) How ambient intelligence will improve habitability and energy efficiency in buildings, *Ambient intelligence*, pp. 63-80. New York, United States of America: Springer.
Ariffin, A.S., Raji, F. and Baqutaya, S. (2016) Affordable housing policy: Issues and challenges among middle-income groups. *International Journal of Social Science and Humanity*, **6**(6), 433.
Ariyan, L. (2020) *Financing for resilient and green urban solutions in Tshwane, South Africa* [Online]. United Nations Human Settlements Programme. Available: https://unhabitat.org/south-africa#:~:text=its%20population%20...-,The%20Republic%20of%20South%20Africa%20is%20one%20of%20the%20most,to%20around%2080%25%20by%202050. [Accessed October 16, 2021].
Arman, M., Pullen, S., Wilson, L., Zillante, G. and Zuo, J. (2009) Challenges of responding to sustainability with implications for affordable housing. *Ecological Economics*, **68**(12), 3034-3041.
Awasthi, A.K., Cheela, V.R.S., D’Adamo, I., Islam, M.R., Johnson, M., Iacovidou, E., Li, J., Miller, T.R., Parajuly, K., Parchomenko, A., Radhakrishan, L., Zhao, M. and Zhang, C. (2021) Zero waste approach towards a sustainable waste management. *Resources, Environment and Sustainability*, **3**(March), 100014.
Badyina, A. and Golubchikov, O. (2012) *Sustainable housing for sustainable cities: a policy framework for developing countries*.
Baiche, B., Ogden, R. and Walliman, N. (2006) Compliance with building regulations in England and Whales. *Structural Survey*, **24**(4), 279-299.

Baker, L., Burton, J., Trollip, H. and Godinho, C. (2015) *The political economy of decarbonisation: Exploring the dynamics of South Africa's electricity sector*. Cape Town, South Africa: University of Cape Town.

Balouktsi, M., Birgisdottir, H., Frischknecht, R., Habert, G., Lützkendorf, T., Passer, A., Rasmussen, F.N., Röck, M. and Saade, M.R.M. (2020) Embodied GHG emissions of buildings – The hidden challenge for effective climate change mitigation. *Applied Energy*, **258**, 114107.

Barnes, J.M., Govender, T. and Pieper, C.H. (2011) Housing conditions, sanitation status and associated health risks in selected subsidized low-cost housing settlements in Cape Town, South Africa. *Habitat International*, **35**(2), 335-342.

Bekkouche, S., Cherier, M., Hamdani, M., Benamrane, N., Benouaz, T. and Yaiche, M. (2013) Thermal resistances of air in cavity walls and their effect upon the thermal insulation performance. *International Journal of Energy and Environment (Print)*, **4**(3), 459-466.

Belussi, L., Barozzi, B., Bellazzi, A., Danza, L., Devitofrancesco, A., Fanciulli, C., Ghellere, M., Guazzi, G., Meroni, I. and Salamone, F. (2019) A review of performance of zero energy buildings and energy efficiency solutions. *Journal of building engineering*, **25**(September), 100772.

Better Buildings Partnership (2013) *Green lease toolkit* [Online]. Available: https://www.betterbuildingspartnership.co.uk/green-lease-toolkit [Accessed March 12, 2023].

Biron, C. (2013) *World Bank, IMF link urbanisation with development* [Online]. Available: https://www.globalissues.org/news/2013/04/18/16354 [Accessed Àpril 04, 2022].

Biwole, P.-H., Fardoun, F. and Souayfane, F. (2016) Phase change materials (PCM) for cooling applications in buildings: A review. *Energy and Buildings*, **129**(October), 396-431.

Biyik, E., Araz, M., Hepbasli, A., Shahrestani, M., Yao, R., Shao, L., Essah, E., Oliveira, A.C., Del Cano, T. and Rico, E. (2017) A key review of building integrated photovoltaic (BIPV) systems. *Engineering science and technology, an international journal*, **20**(3), 833-858.

Black, A.W. (2004) The Quest for Sustainable, Healthy Communities. *Australian Journal of Environmental Education*, **20**(1), 33-44.

Bloom, D.E., Canning, D. and Fink, G. (2008) Urbanization and the wealth of nations. *Science*, **319**(5864), 772-775.

Bolt, G., Phillips, D. and Van Kempen, R. (2010) Housing policy,(de) segregation and social mixing: An international perspective. *Housing Studies*, **25**(2), 129-135.

Branson, G., Lam, D. and Leibbrandt, M. (2012) Education and inequality: The South African case. In: University of Cape Town, 1-29.

BREEAM (2023) *How BREEAM works* [Online]. Available: https://bregroup.com/products/breeam/how-breeam-works/ [Accessed February 22, 2023].

Brent, A., Kovacic, Z., Musango, J. and Smit, S. (2017) Conceptualising slum in an urban African context. *Cities*, **62**(February), 107-119.

Brinkmann, S. (2014) Unstructured and semi-structured interviewing. *In:* Leavy, P. (Ed.), *The Oxford handbook of qualitative research*, pp. 277-299. Oxford, United Kingdom: Oxford University Press.

Brundtland, G.H. (1987) *Report of the World Commission on environment and development:" our common future."*. UN.

BusinessTech (2023) *Nersa approaves massive electrcity price hike for 2023* [Online]. Available: https://businesstech.co.za/news/energy/655825/nersa-approves-massive-electricity-price-hike-for-2023/ [Accessed February 19, 2023].

Butcher, S. (2020) Creating a gap that can be filled: Constructing and territorializing the affordable housing submarket in Gauteng, South Africa. *Environment and Planning A: Economy and Space*, **52**(1), 173-199.
CAHF (2020a) *South Africa Housing market report - 2020* [Online]. Available: https://housingfinanceafrica.org/app/uploads/2021/03/Citymark-National-Property-Market-Report-3-March-2021-FINAL.pdf [Accessed October 23, 2021].
CAHF (2020b) *Housing finance in Africa: A review of Africa's affordable housing fincancing in Africa* [Online]. Available: https://housingfinanceafrica.org/app/uploads/2021/02/2020_CAHF_YEARBOOK_COMP-2.pdf [Accessed October 09, 2021].
Caldeira, T. (2017) Periheral urbanisation: Autoconstruction, trasnversal logics, and politics in cities of the global south. *Environment and Planning D: Society and Space*, **35**(1), 3-20.
Castleberry, A. and Nolen, A. (2018) Thematic analysis of qualitative research data: Is it as easy as it sounds? *Currents in pharmacy teaching and learning*, **10**(6), 807-815.
Chan, A.P.C. and Adabre, M.A. (2019) Bridging the gap between sustainable housing and affordable housing: The required critical success criteria (CSC). *Building and Environment*, **151**(March), 112-125.
Chang, R., Gan, X., Wang, J., Wen, T., Wu, P. and Zuo, J. (2017) How affordable housing becomes more sustainable? A stakeholder study. *Journal of Cleaner Production*, **162**(2017), 427-437.
Charoenkit, S. and Kumar, S. (2014) Environmental sustainability assessment tools for low carbon and climate resilient low income housing settlements. *Renewable and Sustainable Energy Reviews*, **38**(October), 509-525.
Charron, R. (2005) *A review of low and net-zero energy solar home initiatives* [Online]. Available: https://www.researchgate.net/profile/Remi-Charron/publication/228560432_A_Review_of_Low_and_Net-Zero_Energy_Solar_Home_Initiatives/links/5457adda0cf26d5090ab4e62/A-Review-of-Low-and-Net-Zero-Energy-Solar-Home-Initiatives.pdf [Accessed March 13, 2023].
Chastas, P., Theodosiou, T., Kontoleon, K.J. and Bikas, D. (2018) Normalising and assessing carbon emissions in the building sector: A review on the embodied CO2 emissions of residential buildings. *Building and Environment*, **130**(February), 212-226.
Chauhan, R.S. (2022) Unstructured interviews: are they really all that bad? *Human Resource Development International*, **25**(4), 474-487.
Chen, S.-J., Wey, W.-M. and Zhang, H. (2017) Demand-Oriented Design Strategies for Low Environmental Impact Housing in the Tropics. *Sustainability*, **9**(9), 1614-1635.
Cheung, C.K., Fuller, R.J. and Luther, M.B. (2005) Energy-efficient envelope design for high-rise apartments. *Energy and Buildings*, **37**(1), 37-48.
Cheung, G. and Davies, P.J. (2017) In the transformation of energy systems: what is holding Australia back? *Energy Policy*, **109**(October), 96-108.
Choguill, C.L. (2007) The search for policies to support sustainable housing. *Habitat International*, **31**(1), 143-149.
Cirolia, L. and Hoek-Smit, M.C. (2019) *Opening-up the lower-middle income housing market in South Africa: The role of demand-side subsides*. South Africa: World Bank.
Cliffe Dekker Hofmyer (2021) *Giving the green light - opportunities for renewable energy capex following increased embedded electricity generation limit*

[Online]. Available: https://www.cliffedekkerhofmeyr.com/en/news/publications/2021/Tax/Tax-Alert-24-June-2021-Giving-the-green-light-opportunities-for-renewable-energy-capex-following-increased-embedded-electricity-generation-limit.html [Accessed 05 March, 2023].

Climate Action Tracker (2022) *South Africa overall rating: insufficient* [Online]. Available: https://climateactiontracker.org/countries/south-africa/ [Accessed February 12, 2023].

Climatebiz (2023) *Average peak sun hours (South Africa)* [Online]. Available: https://climatebiz.com/average-peak-sun-hours-south-africa/ [Accessed January, 15, 2024].

Coetzee, D. and Brent, A. (2015) Perceptions of professional practitioners and property developers relating to the costs of green buildings in South Africa. *Journal of the South African Institution of civil engineering*, **57**(4), 12-19.

Cole, R.J. and Jose Valdebenito, M. (2013) The importation of building environmental certification systems: international usages of BREEAM and LEED. *Building Research & Information*, **41**(6), 662-676.

Collins, D. (2019) Green leases and green leasing in theory and in practice: a state of the art review. *Facilities*, **37**(11/12), 813-824.

Conlon, B., Hendron, B., Hong, T., German, A., Lee, S.H., McKenzie, L. and Wei, M. (2021) Approaches to cost-effective near-net zero energy new homes with time-of-use value of energy and battery storage. *Advances in Applied Energy*, **2**(April), 100018.

Connell, J.P. and Kubisch, A.C. (1998) Applying a theory of change approach to the evaluation of comprehensive community initiatives: progress, prospects, and problems. *New approaches to evaluating community initiatives*, **2**(15-44), 1-16.

Corbin, J. and Anselm, S. (2015) Practical considerations for getting started, *Basics of qualitative research: Techniques and procedures for developing grounded theory*, 4 edn., pp. 31-57. London, United Kingdom: Sage.

Cortesão, J., Jimenez, M.S., Lenzholzer, S. and Walker, R. (2023) Early-stage design of a low-embodied carbon and cost-effective green facade system. *Journal of building engineering*, **72**(August), 106588.

Coryn, C.L., Noakes, L.A., Westine, C.D. and Schröter, D.C. (2011) A systematic review of theory-driven evaluation practice from 1990 to 2009. *American journal of Evaluation*, **32**(2), 199-226.

Coşkun, K. (2020) A new explanation for the conflict between constructivist and objectivist grounded theory. *International Journal of Qualitative Methods*, **19**(July), 1-5.

Crawley, D., Deru, M., Torcellini, P. and Pless, S. (2006) *Zero energy buildings: a critical look at the definition*. Colorado, United States: National Renewable Energy Lab.

Cropper, M.L., de la Chesnaye, F.C., Murray, B.C. and Reilly, J.M. (2014) How effective are US renewable energy subsidies in cutting greenhouse gases? *American Economic Review*, **104**(5), 569-574.

Crossan, F. (2003) Research philosophy: towards an understanding. *Nurse Researcher (through 2013)*, **11**(1), 46-55.

Cui, Y., Dong, B., Guo, S., Hu, S. and Yan, D. (2017) A survey on energy consumption and energy usage behavior of households and residential building in urban China. *Energy and Buildings*, **148**(August), 366-378.

D'Agostino, D. and Parker, D. (2018) A framework for the cost-optimal design of nearly zero energy buildings (NZEBs) in representative climates across Europe. *Energy*, **149**(April), 814-829.

D'Agostino, D. and Mazzarella, L. (2019) What is a Nearly zero energy building? Overview, implementation and comparison of definitions. *Journal of building engineering*, **21**(January), 200-212.
D'Oca, S., Corgnati, S.P. and Buso, T. (2014) Smart meters and energy savings in Italy: Determining the effectiveness of persuasive communication in dwellings. *Energy Research & Social Science*, **3**(September), 131-142.
Dainty, A. (2008) Methodological pluralism in construction management research. *Advanced research methods in the built environment*, **1**(N/A), 1-13.
Dainty, A.R., Gibb, A.G. and Pan, W. (2012) Establishing and weighting decision criteria for building system selection in housing construction. *Journal of Construction Engineering and Management*, **138**(11), 1239-1250.
David, B. (2015) *What is ethics in research & why is it important?* [Online]. Available: http://dspace.sjc.ac.in/bitstream/123456789/15041/1/What%20is%20Ethics%20in%20Research%20%26%20Why%20is%20it%20important.pdf [Accessed 29 October, 2023].
Davies, R.J. (1981) The spatial formation of the South African city. *GeoJournal*, **2**(2), 59-72.
Dawadi, S., Shrestha, S. and Giri, R.A. (2021) Mixed-methods research: A discussion on its types, challenges, and criticisms. *Journal of Practical Studies in Education*, **2**(2), 25-36.
deMarrais, K. (2003) Qualitative interview studies: Learning through experience, *Foundations for research: Methods of inquiry in education and social science*, pp. 51-68. New Jersey, United States of America: Routledge.
Dempsey, N., Bramley, G., Power, S. and Brown, C. (2011) The social dimension of sustainable development: Defining urban social sustainability. *Sustainable Development*, **19**(5), 289-300.
Deng, S., Wang, R.a. and Dai, Y. (2014) How to evaluate performance of net zero energy building–A literature research. *Energy*, **71**(July), 1-16.
Deparment of Environemental Affairs: Republic of South Africa (2014) *GHG national inventory report South Africa 2000-2010* [Online]. Available: https://www.environment.gov.za/sites/default/files/reports/2000_2010_nationalghginventoryreport.pdf [Accessed October 16, 2021].
Department of Energy (2018) *Aggregated historical energy balances* [Online]. Available: http://www.energy.gov.za/files/media/Energy_Balances.html [Accessed September 25, 2021].
Department of Forestry Fisheries and the Environment (2024) *South Africa's 2021 grid emission factors report*. South Africa: Retrieved from https://www.dffe.gov.za/sites/default/files/legislations/southafrica2021gridemissionfactorsreport_g50071_gon4317.pdf.
Department of Mineral Resources and Energy (2020) *National Energy Act, No. 34 of 1998 as amended 2020* [Online]. Available: https://www.gov.za/sites/default/files/gcis_document/202012/43972gon700.pdf [Accessed 15 June, 2022].
Dezhi, L., Hongxia, C., Hui, E.C.-M., Kai, G., Yanchao, C. and Yang, J. (2016) Assessing the integrated sustainability of a public rental housing project from the perspective of complex eco-system. *Habitat International*, **53**(April), 546-555.
Dikmen, Ç. and Gültekin, A. (2011) Usage of renewable energy resources in buildings in the context of sustainability. *Mühendislik Bilimleri ve Tasarım Dergisi*, **1**(3), 96-100.

Doling, J., Tolentino, J. and Vandenberg, P. (2013) Housing and housing finance-A review of the links to economic development and poverty reduction. *Asian Development Bank Economics Working Paper Series*, **22**(April), 17-26.

Donnelly, J.P. and Trochim, W.M. (2001) *Ethics in research* [Online]. Available: https://conjointly.com/kb/ethics-in-research/ [Accessed November 5, 2023].

Doody, O. and Noonan, M. (2013) Preparing and conducting interviews to collect data. *Nurse researcher*, **20**(5), 1-10.

Drummond, M. (2023) *Africa housing finance yearbook 2022: South Africa* [Online]. Available: chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://housingfinanceafrica.org/app/uploads/2022/12/South-Africa.pdf [Accessed June 17, 2023].

Duffy, J., Hardy, J. and Hauman, M. (2020) *Sustainability-linked loan or green loan: Which? when? Why?* [Online]. Available: https://www.whitecase.com/insight-alert/sustainability-linked-loan-or-green-loan-which-when-why [Accessed March 12, 2023].

Dumay, J. and Qu, S.Q. (2011) The qualitative research interview. *Qualitative Research in Accounting & Management*, **8**(3), 238-264.

Duschl, R. and Lythcott, J. (1990) Qualitative research: From methods to conclusions. *Science Education*, **74**(4), 445-460.

Echendu, A.J. and Okafor, P.C.C. (2021) Smart city technology: a potential solution to Africa's growing population and rapid urbanization? *Development Studies Research*, **8**(1), 82-93.

Eizenberg, E. and Jabareen, Y. (2017) Social sustainability: A new conceptual framework. *Sustainability*, **9**(1), 68.

Fantucci, S. and Serra, V. (2019) Investigating the performance of reflective insulation and low emissivity paints for the energy retrofit of roof attics. *Energy and Buildings*, **182**(January), 300-310.

Fellows, R.F. and Liu, A.M. (2015) *Research methods for construction*. 4 ed. Chichester, United Kingdom: John Wiley & Sons.

Fouka, G. and Mantzorou, M. (2011) What are the major ethical issues in conducting research? Is there a conflict between the research ethics and the nature of nursing? *Health Science Journal*, **5**(1), 3-14.

Frels, R.K. and Onwuegbuzie, A.J. (2013) Administering quantitative instruments with qualitative interviews: A mixed research approach. *Journal of Counseling & Development*, **91**(2), 184-194.

Fullan, M. (2007) Change theory as a force for school improvement, *Intelligent leadership*, pp. 27-39. Perth, Australia: Springer.

Furchtgott-Roth, D. (2023) *Corrupt power sector strangles South Africa* [Online]. Available: https://www.forbes.com/sites/dianafurchtgott-roth/2023/01/11/corrupt-power-sector-strangles-south-africa/?sh=54902fee5f30 [Accessed February 19, 2023].

Gan, Q. and Hill, R.J. (2009) Measuring housing affordability: Looking beyond the median. *Journal of Housing Economics*, **18**(2), 115-125.

Ganiyu, B.O., Fapohunda, J.A. and Haldenwang, R. (2017) Sustainable housing financing model to reduce South Africa housing deficit. *International Journal of Housing Markets and Analysis*, **10**(3), 410-430.

GBCSA (2023) *Other certification tools* [Online]. Available: https://gbcsa.org.za/certify/other-certification-rating-tools/#:~:text=Custom%20GBCSA%20Green%20Star%20certifications,EWP%20or%20the%20EDGE%20tool. [Accessed 18 November, 2023].

Geertman, S., Lin, Y. and Zhang, X. (2015) Toward smart governance and social sustainability for Chinese migrant communities. *Journal of Cleaner Production*, **107**(November), 389-399.
Ghaffar, M.M.A.A. and El Aziz, N.A.A. (2021) Urban form and economic sustainability in housing projects. *Journal of Engineering and Applied Science*, **68**(November), 1-16.
Gibson, R.B. (2010) Beyond the pillars: sustainability assessment as a framework for effective integration of social, economic and ecological considerations in significant decision-making. *Journal of Environmental Assessment Policy and Management*, **8**(3), 259-280.
Giddings, B., Hopwood, B. and O'Brien, G. (2002) Environment, economy and society: fitting them together into sustainable development. *Sustainable Development*, **10**(4), 187-196.
Gilbert, A. (2004) Helping the poor through housing subsidies: lessons from Chile, Colombia and South Africa. *Habitat International*, **28**(1), 13-40.
Glaser, G. (2012) Base sustainable development goals on science. *Nature*, **491**(7422), 35-35.
Gong, X., Akashi, Y. and Sumiyoshi, D. (2012) Optimization of passive design measures for residential buildings in different Chinese areas. *Building and Environment*, **58**(December), 46-57.
Goodland, R. and Daly, H. (1996) Environmental sustainability: universal and non-negotiable. *Ecological Applications*, **6**(4), 1002-1017.
gosolar (2023) *What you get with gosolar* [Online]. Available: https://www.gosolr.co.za/what-you-get [Accessed 05 March, 2023].
Gouveia, J.R., Silva, E., Mata, T.M., Mendes, A., Caetano, N.S. and Martins, A.A. (2020) Life cycle assessment of a renewable energy generation system with a vanadium redox flow battery in a NZEB household. *Energy Reports*, **6**(February), 87-94.
Gray, D.E. (2014) *Doing research in the real world*. 3 ed. London, England: Sage.
Green Building Alliance (2022) *Green leasing* [Online]. Available: https://gba.org/resources/green-building-methods/processes/green-leasing/ [Accessed March 12, 2023].
Green Building Council of South Africa (2021) *Certify: Credible and objective measurement for green buildings in South Africa & Africa* [Online]. Available: https://gbcsa.org.za/certify/ [Accessed September 14, 2021].
Greener, I. (2011) *Designing social research: A guide for the bewildered*. *Designing Social Research*, London, England: Sage Plublications Inc.
Greenland, S.J. (2019) Future sustainability, innovation and marketing: A framework for understanding impediments to sustainable innovation adoption and corporate social responsibility. In Proceedings of *The components of sustainable development*, Singapore, 63-80.
Griffiths, K., Boyle, C. and Henning, T.F. (2020) Infrastructure sustainability rating tools–exploring opportunities for the engineering profession based on international research. *Australian journal of civil engineering*, **18**(1), 18-28.
Gumede, M. (2023) *Poutltry sector warns of rising prices fue to load-shedding* [Online]. Available: https://www.businesslive.co.za/bd/national/2023-01-16-poultry-sector-warns-of-rising-prices-due-to-load-shedding/#:~:text=The%20industry%20is%20calling%20for,of%20rising%20costs%20on%20consumers&text=SA's%20poultry%20industry%20has%20warned,hamstrung%20by%20intensified%20load%2Dshedding. [Accessed February 19, 2023].

Güneralp, B. and Seto, K.C. (2012) Can gains in efficiency offset the resource demands and CO2 emissions from constructing and operating the built environment? *Applied Geography*, **32**(1), 40-50.
Habitat for Humanity (2021) *What is affordable housing* [Online]. Available: https://www.habitat.org/emea/about/what-we-do/affordable-housing [Accessed 01 May, 2022].
Hakiminejad, A., Fu, C. and Mohammadzadeh Titkanlou, H. (2015) A critical review of sustainable built environment development in Iran. *In*, *Proceedings of the Institution of Civil Engineers-Engineering Sustainability*. Thomas Telford Ltd, Vol. 168, 105-119.
Hall, R. (2013) Mixed methods: In search of a paradigm. *Conducting research in a changing and challenging world*, **N/A**(January), 71-78.
Hannoudi, L., Saleeb, N. and Dafoulas, G. (2024) The impact of glass properties on the energy efficiency and embodied carbon of multi-angled façade systems. *Journal of Cleaner Production*, **437**(January), 140725.
Heale, R. and Twycross, A. (2015) Validity and reliability in quantitative studies. *Evidence-based Nursing*, **18**(3), 66-67.
Hesse, H.C., Martins, R., Musilek, P., Naumann, M., Truong, C.N. and Jossen, A. (2017) Economic optimization of component sizing for residential battery storage systems. *Energies*, **10**(7), 835.
Hestnes, A.G. and Sartori, I. (2007) Energy use in the life cycle of conventional and low-energy buildings: A review article. *Energy and Buildings*, **39**(3), 249-257.
Högberg, L. (2014) Building sustainability: studies on incentives in construction and management of real estate. In, Unpublished Doctoral Thesis: Royal Institute of Technology.
Holloway, I. and Todres, L. (2003) The status of method: flexibility, consistency and coherence. *Qualitative Research*, **3**(3), 345-357.
Hulchanski, J.D. (1995) The concept of housing affordability: Six contemporary uses of the housing expenditure-to-income ratio. *Housing Studies*, **10**(4), 471-491.
Ibn-Mohammed, T., Greenough, R., Taylor, S., Ozawa-Meida, L. and Acquaye, A. (2013) Operational vs. embodied emissions in buildings—A review of current trends. *Energy and Buildings*, **66**(November), 232-245.
Ibrahimu, K., Mulalo, R. and Nwobodo-Anyadiegwu, E. (2018) Project cost overrun in the South African construction sector: A case study of Johannesburg Metropolis. *In*, *Proceedings of the International Conference on Industrial Engineering and Operations Management Pretoria/Johannesburg, South Africa*, 1263-1270.
Illankoon, I.C.S., Tam, V.W., Le, K.N., Tran, C.N. and Ma, M. (2019) Review on green building rating tools worldwide: Recommendations for Australia. *Journal of Civil Engineering and Management*, **25**(8), 831-847.
International Energy Agency (2018) *Definition and simulation of occupant behavior in buildings* [Online]. Available: http://annex66.org/sites/default/files/2018FinalReport/Annex%2066%20Final%20Report%20-%20read.pdf [Accessed February 07, 2023].
International Energy Agency (2020) *Energy technology perspectives 2020* [Online]. Available: https://bit.ly/4dYU2sd [Accessed 24 September, 2021].
International Energy Agency (2021) *Net zero by 2050: A roadmap of global energy sector* [Online]. Available: https://iea.blob.core.windows.net/assets/beceb956-0dcf-4d73-89fe-1310e3046d68/NetZeroby2050-ARoadmapfortheGlobalEnergySector_CORR.pdf [Accessed September 4, 2021].

International Monetary Fund (2024) *Income inequality: Introduction to inequality* [Online]. Available: https://www.imf.org/en/Topics/Inequality/introduction-to-inequality [Accessed May 28, 2025].
Isalou, A.A., Litman, T. and Shahmoradi, B. (2014) Testing the housing and transportation affordability index in a developing world context: A sustainability comparison of central and suburban districts in Qom, Iran. *Transport Policy*, **33**(May), 33-39.
Iyer-Raniga, U. (2019) Zero energy in the built environment: A holistic understanding. *Applied Sciences*, **9**(16), 3375.
Jabareen, Y.R. (2006) Sustainable urban forms: Their typologies, models, and concepts. *Journal of planning education and research*, **26**(1), 38-52.
Javernick-Will, A. and Kaminsky, J. (2015) Theorizing the internal social sustainability of sanitation organizations. *Journal of Construction Engineering and Management*, **141**(2), 04014071.
Jomehzadeh, F., Hussen, H.M., Calautit, J.K., Nejat, P. and Ferwati, M.S. (2020) Natural ventilation by windcatcher (Badgir): A review on the impacts of geometry, microclimate and macroclimate. *Energy and Buildings*, **226**(November), 110396.
Jones Lang LaSalle (2019) *Affordable housing in India: An inclusive approach to sheltering the bottom of the pyramid*. New Delhi, India: National Institute of Urban Affairs.
Jung, H.-J., Lee, J.-W., Lee, J., Park, J.-Y. and Yoon, Y. (2013) Optimization of building window system in Asian regions by analyzing solar heat gain and daylighting elements. *Renewable Energy*, **50**(February), 522-531.
Kalugina, A. (2016) *Affordable housing policies: An overview* [Online]. Available: https://ecommons.cornell.edu/bitstream/handle/1813/70761/Affordable_Housing_Overview.pdf?sequence=1&isAllowed=y [Accessed January 06, 2023].
Kapoulas, A. and Mitic, M. (2012) Understanding challenges of qualitative research: Rhetorical issues and reality traps. *Qualitative Market Research: An International Journal*, **15**(4), 354-368.
Kazem, M., Ezzeldin, S. and Tolba, O. (2022) Life-cycle cost analysis for façade retrofit measures of residential buildings in Cairo. *Indoor and Built Environment*, **31**(4), 913-928.
Kenny, A. (2015) The rise and fall of Eskom and how to fix it now. *Policy Bulletin*, **2**(18), 1-22.
Knight, A. and Ruddock, L. (2009) *Advanced research methods in the built environment*. United England, England: John Wiley & Sons.
Koebel, C.T. (2008) Innovation in Homebuilding and the Future of Housing. *Journal of the American Planning Association*, **74**(1), 45-58.
Kölbel, J.F. and Lambillon, A.-P. (2023) Who pays for sustainability? An analysis of sustainability-linked bonds. *In*, *AFA Annual Meeting*, New Orleans, LA, 1-32.
Kopfmüller, J., Brandl, V., Jörissen, J., Paetau, M., Banse, G., Coenen, R. and Grunwald, A. (2001) *Nachhaltige Entwicklung integrativ betrachtet: Konstitutive Elemente, Regeln, Indikatoren*. Berlin, Germany: edition sigma Berlin.
Kothari, C. (2004) *Research Methodology: Methods and techniques 2nd revised edition*. New Delhi, India: New Age International Publishers.
Krauss, S.E. (2005) Research paradigms and meaning making: A primer. *The Qualitative Report*, **10**(4), 758-770.
Kumar, N.M., Chopra, S.S., Chand, A.A., Elavarasan, R.M. and Shafiullah, G. (2020) Hybrid renewable energy microgrid for a residential community: A techno-economic and environmental perspective in the context of the SDG7. *Sustainability*, **12**(10), 3944.

Landman, K. and Plessis, C.A.d. (2002) *Sustainability analysis of human settelements in South Africa* [Online]. Available: http://researchspace.csir.co.za/dspace/bitstream/handle/10204/3522/Du%20Plessis_2002.pdf;jsessionid=5401A497D397DDA30FC2FBEE15BA71C7?sequence=1 [Accessed October 16, 2021].

Langston, Y.L. and Langston, C.A. (2008) Reliability of building embodied energy modelling: an analysis of 30 Melbourne case studies. *Construction Management and Economics*, **26**(2), 147-160.

Laski, J. and Burrows, V. (2017) *From thousands to billions*. World Green Building Council.

Lavrakes, P. and Roller, M. (2015) *Applied qualitative research design: A total quality framework approach*. New York, United States of America: The Guilford Press.

Law, A.M. (2022) How to build valid and credible simulation models. *In*, *2022 Winter Simulation Conference (WSC)*. IEEE, 1283-1295.

LEED (2021) *LEED scorecoard* [Online]. Available: https://www.usgbc.org/leed-tools/scorecard [Accessed October 21, 2021].

Leininger, J. and Tosun, J. (2017) Governing the interlinkages between the sustainable development goals: Approaches to attain policy integration. *Global Challenges*, **1**(9), 1-12.

Lenoke, M. (2017) *The impact of load shedding on the economic growth of South Africa* [Online]. North-West University (South Africa). Available: https://bit.ly/3Yv5QOr [Accessed February 11, 2023].

Levermore, G.J. (2008) A review of the IPCC assessment report four, part 1: the IPCC process and greenhouse gas emission trends from buildings worldwide. *Building Services Engineering Research and Technology*, **29**(4), 349-361.

Lima, L., Trindade, E., Alencar, L., Alencar, M. and Silva, L. (2021) Sustainability in the construction industry: A systematic review of the literature. *Journal of Cleaner Production*, **289**(March), 125730.

Littig, B. and Griessler, E. (2005) Social sustainability: a catchword between political pragmatism and social theory. *International Journal of Sustainable Development*, **8**(July), 65-79.

Livingood, B., Polly, B., Kutscher, C., Macumber, D., Schott, M., Pless, S. and Van Geet, O. (2016) From zero energy buildings to zero energy districts. *Proceedings of the 2016 American Council for an Energy Efficient Economy Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, USA*(August), 21-26.

Lonwabo, K. (2022) *Understanding the load shedding stages* [Online]. Available: https://albertonrecord.co.za/?p=333087 [Accessed February 19, 2023].

MacKillop, F. (2013) Sustainable as a basis of affordable? Understanding the affordability 'crisis' in Australian housing. *Australian Planner*, **50**(1), 2-12.

Maclennan, D., Ong, R. and Wood, G. (2015) *Making connections: housing, productivity and economic development*. Australian Housing and Urban Research Insitute:

Mahlangu, A. (2023). Available: https://www.businesslive.co.za/bd/companies/2023-01-16-blackouts-tariff-hikes-weigh-on-businesses-says-werksmans/#:~:text=Rolling%20power%20blackouts%20and%20the,practice%20group%20at%20Werksmans%20Attorneys. [Accessed February 19, 2023].

Maliene, V. and Mulliner, E. (2015) An Analysis of Professional Perceptions of Criteria Contributing to Sustainable Housing Affordability. *Sustainability*, **7**(1), 248-270.

Mann, K. (2021) *R-value and U-value: What value are they to you* [Online]. Available: https://indowwindows.com/resources/blog/r-value-vs-u-value/#:~:text=A%20standard%20double%2Dpane%20window,than%20to%20an%20insulated%20wall. [Accessed 07 April, 2023].

Mannan, S. and Afni, M. (2020) *Best practices of Semi-structured interview method* [Online]. Available: https://www.researchgate.net/profile/Samsul-Mannan/publication/341232398_Best_practices_of_Semi-structured_interview_method/links/5eb4f70192851cd50da139bd/Best-practices-of-Semi-structured-interview-method.pdf [Accessed July, 27, 2023].

Mao, Y., Purvis, B. and Robinson, D. (2019) Three pillars of sustainability: in search of conceptual origins. *Sustainability Science*, **14**(3), 681-695.

Marais, L., Awuzie, B., Cloete, J., Napier, M. and Greyling, E. (2020) A Tale of Two Markets: Unequal Access to Private Property in a South African City. *Tijdschrift voor economische en sociale geografie*, **111**(1), 80-98.

Marsh, E., Allen, S. and Hattam, L. (2023) Tackling uncertainty in life cycle assessments for the built environment: A review. *Building and Environment*, **231**(March), 109941.

Marszal, A.J., Heiselberg, P., Bourrelle, J.S., Musall, E., Voss, K., Sartori, I. and Napolitano, A. (2011) Zero Energy Building – A review of definitions and calculation methodologies. *Energy and Buildings*, **43**(4), 971-979.

Marthinusen, L. (2023) *How many solar panels do I need?* [Online]. Available: https://www.solarwow.co.za/blog/how-many-solar-panels/#:~:text=On%20average%2C%20South%20Africa%20experiences,Europe%20and%20the%20United%20Kingdom. [Accessed February 18, 2024].

Marutlulle, N. (2021) A critical analysis of housing inadequacy in South Africa and its ramifications. *South Africa's Public Delivery and Performance Review*, **9**(1), a372.

MaslakÇI, A. and Sürücü, L. (2020) Validity and reliability in quantitative reserach. *Business & Management Studies: An International Journal*, **8**(3), 2694-2726.

Massey, R. (2020) Urban renewal in South African cities. *In:* Massey, R. and Gunter, A. (Eds.), *Urban Geography in South Africa: Perspectives and Theory*, pp. 265-282. Cham: Spring International Publishing.

McGaffin, R. (2018) Housing in Cape Twon in 2018 - A draft discussion document. In, Unpublished, 1-10.

McGranahan, G. and Satterthwaite, D. (2014) *Urbanisation concepts and trends*. Vol. 220, London, England: JSTOR.

Meen, G. (2018) *How should housing affrodablility be measured?* [Online]. Available: https://housingevidence.ac.uk/wp-content/uploads/2018/10/R2018_02_01_How_to_measure_affordability_v2.pdf [Accessed 15 November, 2023].

Meijer, F. and Visscher, H. (2007) Dynamics of building regulations in Europe. In Proceedings of *ENHR 2007 International Conference on Sustainable Urban Areas*, 25-28 June 2007, Rotterdam.

Meyer, E., Simon, M. and Tangwe, S.I. (2019) Quantification of the viability of residential air source heat pump water heaters as potential replacement for geysers in South Africa. *Journal of Engineering, Design and Technology*, **17**(2), 456-470.

Mingfang, T. (2002) Solar control for buildings. *Building and Environment*, **37**(7), 659-664.

Minunno, R., O'Grady, T., Morrison, G.M. and Gruner, R.L. (2021) Investigating the embodied energy and carbon of buildings: A systematic literature review and meta-analysis of life cycle assessments. *Renewable and Sustainable Energy Reviews*, **143**(June), 110935.

Missimer, M., Robèrt, K.-H. and Broman, G. (2017) A strategic approach to social sustainability – Part 1: exploring the social system. *Journal of Cleaner Production*, **140**(January), 32-41.
Moeti, K. (2023) *South Africa's deadly housing crisis* [Online]. Available: https://bit.ly/4eTMnws [Accessed June 17, 2023].
Moghayedi, A. and Awuzie, B. (2023) Towards a net-zero carbon economy: A sustainability performance assessment of innovative prefabricated construction methods for affordable housing in Southern Africa. *Sustainable Cities and Society*, **99**(December), 104907.
Moghayedi, A., Hübner, D. and Michell, K. (2022) Achieving sustainability in South African commercial properties: The impact of innovative technologies on energy consumption. *Facilities*(ahead-of-print).
Moghayedi, A., Phiri, C. and Ellmann, A.-M. (2023) Improving sustainability of affordable housing using innovative technologies: Case study of SIAH-Livable. *Scientific African*, **21**(September), e01819.
Moghayedi, A., Awuzie, B., Omotayo, T., Le Jeune, K. and Massyn, M. (2022) Appraising the nexus between influencers and sustainability-oriented innovation adoption in affordable housing projects. *Sustainable Development*, **30**(5), 1117-1134.
Moghayedi, A., Mahachi, J., Lediga, R., Mosiea, T. and Phalafala, E. (2024) Revolutionizing affordable housing in Africa: A comprehensive technical and sustainability study of 3D-printing technology. *Sustainable Cities and Society*, **105**(June), 105329.
Moghayedi, A., Awuzie, B., Omotayo, T., Le Jeune, K., Massyn, M., Ekpo, C.O., Braune, M. and Byron, P. (2021) A Critical Success Factor Framework for Implementing Sustainable Innovative and Affordable Housing: A Systematic Review and Bibliometric Analysis. *Buildings*, **11**(8), 317.
Moldan, B., Janoušková, S. and Hák, T. (2012) How to understand and measure environmental sustainability: Indicators and targets. *Ecological Indicators*, **17**(June), 4-13.
Mota, N. (2015) *Housing affordability primer* [Online]. Available: https://www.fanniemae.com/sites/g/files/koqyhd191/files/migrated-files/resources/file/research/datanotes/pdf/housing-insights-111215.pdf [Accessed 31 August, 2022].
Mulliner, E., Smallbone, K. and Maliene, V. (2013) An assessment of sustainable housing affordability using a multiple criteria decision making method. *Omega*, **41**(2), 270-279.
Murshed, M., Rahman, M., Alam, M.S., Ahmad, P. and Dagar, V. (2021) The nexus between environmental regulations, economic growth, and environmental sustainability: linking environmental patents to ecological footprint reduction in South Asia. *Environmental Science and Pollution Research*, **28**(36), 49967-49988.
Mutisya, E. and Yarime, M. (2014) Moving towards urban sustainability in Kenya: a framework for integration of environmental, economic, social and governance dimensions. *Sustainability Science*, **9**(2), 205-215.
Nardelli, A., Deuschle, E., de Azevedo, L.D., Pessoa, J.L.N. and Ghisi, E. (2017) Assessment of Light Emitting Diodes technology for general lighting: A critical review. *Renewable and Sustainable Energy Reviews*, **75**(August), 368-379.
National Treasury (2023) *Solar panel tax incentive for individuals: frequently asked questions* [Online]. Available: https://www.treasury.gov.za/documents/National%20Budget/2023/2023%20B

udget%20FAQs%20-%20Solar%20Panel%20Tax%20Incentive.pdf [Accessed 05 March, 2023].
Nedbank (2020) *SANS 10400-XA Energy usage in buildings: A homeowner's guide to compliance in home design* [Online]. Available: chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.nedbank.co.za/content/dam/nedbank/site-assets/AboutUs/GreenandCaring/SANS%20Guide%20-%20Homeowners%20final.pdf [Accessed 07 April, 2023].
Never, B., Kuhn, S., Fuhrmann-Riebel, H., Albert, J.R., Gsell, S., Jaramillo, M. and Sendaza, B. (2022) Energy saving behaviours of middle class households in Ghana, Peru and the Philippines. *Energy for Sustainable Development*, **68**(June), 170-181.
Next Renewable Generation (2023) *A guide to size a solar system* [Online]. Available: https://nrgeneration.co.za/a-guide-to-size-a-solar-system/ [Accessed 18 February, 2024].
Nydahl, H., Andersson, S., Åstrand, A.P. and Olofsson, T. (2019) Environmental performance measures to assess building refurbishment from a life cycle perspective. *Energies*, **12**(2), 299.
O'Dell, W., Smith, M.T. and White, D. (2004) Weaknesses in current measures of housing needs. *Housing and Society*, **31**(1), 29-40.
OECD (2016) *Green bonds: Mobilising the debt capital markets for a low-carbon transition* [Online]. Available: https://www.oecd.org/environment/cc/Green%20bonds%20PP%20%5Bf3%5D%20%5Blr%5D.pdf [Accessed March 12, 2023].
OECD Environment Ministers (2001) *OECD Environmental strategy for the first decade of the 21st century*. Paris, France: Intergovermental Organisation Report.
Omrany, H. and Marsono, A.K. (2016) Optimization of building energy performance through passive design strategies. *British Journal of Applied Science & Technology*, **13**(6), 1-16.
Oner, C. (2020) *Inflation: Prices on the rise* [Online]. Available: https://www.imf.org/external/pubs/ft/fandd/basics/inflat.htm#:~:text=To%20the%20extent%20that%20households,for%20the%20standard%20of%20living. [Accessed 31 August, 2022].
Ordoñez, A., Carreras, J., Korolija, I., Zhang, Y. and Coronas, A. (2014) Impact of building geometry on its energy performance depending on climate zones. *In*, *Proceedings of the BSO14: Second Building Simulation and Optimization Conference, London, UK*, 23-24.
Pacheco, R., Ordóñez, J. and Martínez, G. (2012) Energy efficient design of building: A review. *Renewable and Sustainable Energy Reviews*, **16**(6), 3559-3573.
Parliament of Australia (2016) *Housing affordability in Australia* [Online]. Available: https://www.aph.gov.au/about_parliament/parliamentary_departments/parliamentary_library/pubs/briefingbook45p/housingaffordability [Accessed 02 May, 2022].
Patel, C. and Chugan, P.K. (2013) Measuring awareness and preferences of real estate developers for green buildings over conventional buildings. *Consumer Behaviour and Emerging Practices in Marketing, Eds. Jayesh Aagja, Ashiwini K. Awasthi and Sanjay Jain, Institute of Management, Nirma University, Himalaya Publishing House, Mumbai*, **N/A**(January), 332-341.
Patel, J. (2021) Analyzing a Net Zero Energy Building (NZEB) in the Climate Zone of Australia. *Open Science Journal*, **6**(1), 1-19.

Patton, M.Q. (2014) *Qualitative research & evaluation methods: Integrating theory and practice*. 4 ed. California, United States: Sage publications.
PD&R Edge Home (2017) *Defining affordable housing* [Online]. Available: https://www.huduser.gov/portal/pdredge/pdr-edge-featd-article-081417.html [Accessed 02 May, 2022].
Perera, S. and Victoria, M.F. (2018) Managing embodied carbon in buildings: a Pareto approach. *Built Environment Project and Asset Management*, **8**(5), 504-514.
Piao, X. and Managi, S. (2023) Household energy-saving behavior, its consumption, and life satisfaction in 37 countries. *Scientific Reports*, **13**(1), 1382.
Pivo, G. (2013) *The definition of affordable housing: Concerns and related evidence* [Online]. Available: https://bit.ly/4dRD1Qx [Accessed January 06, 2023].
Polèse, M., Stren, R.E. and Stren, R. (2000) *The social sustainability of cities: Diversity and the management of change*. Toronto, United States: University of Toronto press.
Pomponi, F. and Moncaster, A. (2016) Embodied carbon mitigation and reduction in the built environment–What does the evidence say? *Journal of environmental management*, **181**(October), 687-700.
Ponterotto, J.G. (2005) Qualitative research in counseling psychology: A primer on research paradigms and philosophy of science. *Journal of counseling psychology*, **52**(2), 126-136.
Price Editor, J.H. and Murnan Assistant, J. (2004) Research Limitations and the Necessity of Reporting Them. *American Journal of Health Education*, **35**(2), 66-67.
Proctor, E., Silmere, H., Raghavan, R., Hovmand, P., Aarons, G., Bunger, A., Griffey, R. and Hensley, M. (2011) Outcomes for implementation research: conceptual distinctions, measurement challenges, and research agenda. *Administration and policy in mental health and mental health services research*, **38**(October), 65-76.
Purvis, B., Mao, Y. and Robinson, D. (2019) Three pillars of sustainability: in search of conceptual origins. *Sustainability Science*, **14**(3), 681-695.
PWC (2023) *South Africa's just energy transition: moving from planning to action 2023* [Online]. Available: https://www.pwc.co.za/en/press-room/south-africas-just-energy-transition-moving-from-planning-to-action-in-2023.html [Accessed February 12, 2023].
Qarout, L. (2017) *Reducing the environmental impacts of building materials: Embodied energy analysis of a high-performance building*. The University of Wisconsin-Milwaukee.
Resnik, D.B. (2011) What is ethics in research & why is it important. *National Institute of Environmental Health Sciences*, **1**(10), 49-70.
RICS (2016) *RICS professional guidance, England and Whales Valuation of land for affordable housing, 2nd edition, April 2016*.
RICS (2023) *Whole life carbon assessment (WLCA) for the built environment*. Royal Instituion of Chartered Surveyors.
Robati, M., Oldfield, P., Nezhad, A.A., Carmichael, D.G. and Kuru, A. (2021) Carbon value engineering: A framework for integrating embodied carbon and cost reduction strategies in building design. *Building and Environment*, **192**(April), 107620.
Robinson, S.K. (2020) A global reset of education. *PROSPECTS*, **49**(1), 7-9.
Roeland, M. (2023) *Social housing in South Africa is in trouble - here's why* [Online]. Available: https://bit.ly/4eTMlok [Accessed 18 November, 2023].
Rogers, P., Jalal, K. and Boyd, J. (2007) *An introduction to sustainable development*. London, England: Routledge.

Roh, S., Shin, S. and Tae, S. (2014) Development of building materials embodied greenhouse gases assessment criteria and system (BEGAS) in the newly revised Korea Green Building Certification System (G-SEED). *Renewable and Sustainable Energy Reviews*, **35**(July), 410-421.

Ruparathna, R., Hewage, K. and Sadiq, R. (2016) Improving the energy efficiency of the existing building stock: A critical review of commercial and institutional buildings. *Renewable and Sustainable Energy Reviews*, **53**(January), 1032-1045.

Rural Development and Land Reform: Republic of South Africa (2019) *Draft national spatiel development framework* [Online]. Available: https://www.gov.za/sites/default/files/gcis_document/202002/draftnsdf20jan2020-compressed.pdf [Accessed October 16, 2021].

Rust, K. (2006) *Analysis of South Africa's housing sector performance*. Johannesberg, South Africa: FinMark Trust.

SABS (2021) *The application of the National Building Regulations* [Online]. Available: https://bit.ly/41brjd9 [Accessed 07 May, 2023].

Saidu, A.I. and Yeom, C. (2020) Success Criteria Evaluation for a Sustainable and Affordable Housing Model: A Case for Improving Household Welfare in Nigeria Cities. *Sustainability*, **12**(2), 656.

Salehi, M. (2022) Global water shortage and potable water safety; Today's concern and tomorrow's crisis. *Environment International*, **158**(January), 106936.

Sani, N. (2015) Price to income ratio approach in housing affordability. *J. Bus. Econ. Manag*, **3**(12), 1190-1193.

SANS 10400-XA (2011) The application of the National Building Regulations - Part X: Environmental sustainability - Part XA: Energy usage in buildings. In: Division, S.S., Ed., Pretoria. South Africa.

SANS (2023) *Building regulations (NBR) introduction* [Online]. Available: https://www.sans10400.co.za/ [Accessed 22 April, 2023].

SAPOA (2022) *Operating cost report October 2022*.

Sartori, I., Napolitano, A. and Voss, K. (2012) Net zero energy buildings: A consistent definition framework. *Energy and Buildings*, **48**(May), 220-232.

Saunders, M., Lewis, P. and Thornhill, A. (2015) *Research methods for business students (7th New ed)*. 7th ed. *Research methods for business students*.

Schleich, J., Mills, B. and Dütschke, E. (2014) A brighter future? Quantifying the rebound effect in energy efficient lighting. *Energy Policy*, **72**(September), 35-42.

Schmid, C. and Silva, M. (2015) *Tenlaw: Tenancy law and housing policy in multi-level Europe*. Retrieved from https://www.uni-bremen.de/fileadmin/user_upload/fachbereiche/fb6/fb6/Forschung/ZERP/TENLAW/IntrateamCom/Gesamt_Report.pdf.

Schwartz, D. (2016) The importance of affordable housing to economic competitiveness. *Economic Development Journal*, **15**(1), 40-46.

Schwartz, M. and Wilson, E. (2008) *Who can afford to live in a home? A look at data from the 2006 American Community Survey* [Online]. [Accessed April 16, 2022].

Schwartz, Y., Raslan, R. and Mumovic, D. (2018) The life cycle carbon footprint of refurbished and new buildings – A systematic review of case studies. *Renewable and Sustainable Energy Reviews*, **81**(January), 231-241.

Sev, A. (2009) How can the construction industry contribute to sustainable development? A conceptual framework. *Sustainable Development*, **17**(3), 161-173.

Seyfang, G. (2010) Community action for sustainable housing: Building a low-carbon future. *Energy Policy*, **38**(12), 7624-7633.
Shah, N. (2011) Ethical issues in biomedical research and publication. *Journal of Conservative Dentistry*, **14**(3), 205-207.
Shama, Z.S. and Motlak, J.B. (2019) Indicators for Sustainable housing. *In*, *IOP conference series: materials science and engineering*. IOP Publishing, Vol. 518, 022009.
Sharifzai, M.S., Kitagawa, K., Habib, A.J., Halimee, M.K. and Sakaguchi, D. (2016) Investigation of sustainable and affordable housing policy principles and formulation adoptable in Kabul City, Afghanistan. *Journal of Sustainable development*, **9**(2), 93-126.
Shi, X., Tian, Z., Chen, W., Si, B. and Jin, X. (2016) A review on building energy efficient design optimization rom the perspective of architects. *Renewable and Sustainable Energy Reviews*, **65**(November), 872-884.
Simbanegavi, P. (2021) *Africa housing finance yearbook 2021* [Online]. Available: https://bit.ly/3YxY1Yo [Accessed 27 August, 2022].
South African Government (2023a) *Declaration of a national state of disaster: Impact of severe electricty supply constraint* [Online]. Available: https://www.gov.za/sites/default/files/gcis_document/202302/48009gon3020.pdf [Accessed February 11, 2023].
South African Government (2023b) *National Building Regulations and Building Standards Act 103 or 1977* [Online]. Available: https://www.gov.za/documents/national-building-regulations-and-building-standards-act-16-apr-2015-1302 [Accessed 22 April, 2023].
South African Human Rights Commission (2020) *Fact sheet on the right to adiquate housing* [Online]. Available: https://www.sahrc.org.za/home/21/files/Fact%20Sheet%20on%20the%20right%20to%20adequate%20housing.pdf [Accessed March, 04, 2022].
Standard, U.N.B. (2025) *The pilot version of the UK net zero carbon buildings standard* [Online]. Available: https://www.nzcbuildings.co.uk/pilotversion [Accessed April 28, 2025].
Statistics South Africa (2019) *General Household Survey* [Online]. Available: http://www.statssa.gov.za/publications/P0318/P03182019.pdf [Accessed October 09, 2021].
Statistics South Africa (2022a) *Municipal finances and electricity: 11 years in perpective* [Online]. Available: https://www.statssa.gov.za/?p=15612 [Accessed February 19, 2023].
Statistics South Africa (2022b) *General household survey 2021* [Online]. Available: https://www.statssa.gov.za/publications/P0318/P03182021.pdf [Accessed February 11, 2023].
Steg, L. (2008) Promoting household energy conservation. *Energy Policy*, **36**(12), 4449-4453.
Strandenaes, J.-G. (2017) *The SDGs and HLPF - a new paradigm for civil society* [Online]. Available: https://www.global-value.eu/toolkit/wp-content/uploads/2017/05/9_ppt_Strandenaes_Evaluating-the-Sustainable-Development-Goals-Vienna-Oct-2015.pdf [Accessed 16 October, 2022].
Strauss, M. and Liebenberg, S. (2014) Contested spaces: Housing rights and evictions law in post-apartheid South Africa. *Planning Theory*, **13**(4), 428-448.
Subedi, D. (2016) Explanatory sequential mixed method design as the third research community of knowledge claim. *American Journal of Educational Research*, **4**(7), 570-577.

Swift, P. (2013) *Energy usage & sustainability (SANS 10400X & XA)* [Online]. Available: https://www.sans10400.co.za/energy-usage/ [Accessed 18 November, 2023].
Tanyi, P., Tanga, P.T. and Manomano, T. (2016) Housing problems and programs in South Africa: A literature review. *Journal of Sociology and Social Anthropology*, **7**(2), 111-117.
Tashakkori, A. and Teddlie, C. (2003) Issues and dilemmas in teaching research methods courses in social and behavioural sciences: US perspective. *International journal of social research methodology*, **6**(1), 61-77.
Teja, M.T.V. (2018) Planning and design of net-zero energy residential buidling (NZERB). *International Journal of Advanced in Management, Technology and Engineering Sciences, ISSN*, **8**(4), 576-586.
Tejero, A., Ortiz, J. and Salom, J. (2018) Evaluation of occupancy impact in a residential multifamily nZEB through a high resolution stochastic model. *In*, *Proceedings of the 4th Building Simulation and Optimization Conference, Cambridge, UK*, 11-12.
The Department of Human Settlements (2022) *Official guide to South Africa 2021/22*.
TIPSASA (2022) *SANS 10400XA: 2021 Themeral insulation guide*.
Todes, A. and Turok, I. (2018) Spatial inequalities and policies in South Africa: Place-based or people-centred? *Progress in Planning*, **123**, 1-31.
Tong, Z., Chen, Y., Malkawi, A., Liu, Z. and Freeman, R.B. (2016) Energy saving potential of natural ventilation in China: The impact of ambient air pollution. *Applied Energy*, **179**(October), 660-668.
Tshitereke, C. (2008) *The importance of adequate housing* [Online]. Available: http://bit.ly/4faP9NI [Accessed April, 20, 2022].
Tsioumas, E., Jabbour, N., Koseoglou, M., Sfetkos, I. and Mademlis, C. (2018) Enhanced Effectiveness in the Appliance Scheduling and Energy Storage Control by utilizing the Particle Swarm Technique for a Nearly Zero Energy Building. *In*, *2018 IEEE 4th Southern Power Electronics Conference (SPEC)*. IEEE, 1-7.
Tuli, F. (2010) The basis of distinction between qualitative and quantitative research in social science: Reflection on ontological, epistemological and methodological perspectives. *Ethiopian Journal of Education and Sciences*, **6**(1), 97-108.
Turok, I. (2012) *Urbanisation and development in South Africa: Economic imperatives, spatial distortions and strategic responses*. London, England: Human Settlements Group, International Institute for Environment and ….
Ubarte, I. and Kaplinski, O. (2016) Review of the sustainable built environment in 1998–2015. *Engineering Structures and Technologies*, **8**(2), 41-51.
Un-Habitat (2011) *Affordable land and housing in Asia*. Nairobi, Kenya: UNON.
UN (2023) *CO2 emissions from buildings and construction hit new high, leaving sector off track to decarboniza by 2050: UN* [Online]. Available: https://www.unep.org/news-and-stories/press-release/co2-emissions-buildings-and-construction-hit-new-high-leaving-sector [Accessed January, 15, 2024].
United Nations (2015) *Ssutainable development* [Online]. Available: https://www.un.org/ecosoc/en/sustainable-development [Accessed October 15, 2022].
United Nations (2018a) *68% of the world population projected to live in urban areas by 2050, says UN* [Online]. Available: https://www.un.org/development/desa/en/news/population/2018-revision-of-world-urbanization-prospects.html [Accessed September 12, 2021].

United Nations (2022) *The human right to adequate housing* [Online]. Available: https://www.ohchr.org/en/special-procedures/sr-housing/human-right-adequate-housing#:~:text=Housing%20is%20a%20right%2C%20not,home%20or%20lands%20taken%20away. [Accessed April 04, 2022].
United Nations, D.o.E.a.S.A., Population Division,, (2018b) *The world's cities in 2018 - Data booklet* [Online]. Available: https://www.un.org/development/desa/pd/sites/www.un.org.development.desa.pd/files/files/documents/2020/Jan/un_2018_worldcities_databooklet.pdf [Accessed January, 19, 2023].
United Nations Environment Programme (2009) *Buildings and climate change: Summary for decision makers* [Online]. Available: https://wedocs.unep.org/bitstream/handle/20.500.11822/32152/BCC_SDM.pdf?sequence=1&isAllowed=y [Accessed September 4, 2021].
Van Gulck, L., Wastiels, L. and Steeman, M. (2022) How to evaluate circularity through an LCA study based on the standards EN 15804 and EN 15978. *The International Journal of Life Cycle Assessment*, **27**(12), 1249-1266.
Van Wyk, J. (2012) *Planning law*. Cape Town, South Africa: Juta and Company Ltd.
von Paumgartten, P. (2003) The business case for high performance green buildings: Sustainability and its financial impact. *Journal of Facilities Management*, **2**(1), 26-34.
Walsh, Z., Böhme, J. and Wamsler, C. (2021) Towards a relational paradigm in sustainability research, practice, and education. *Ambio*, **50**(February), 74-84.
Wang, J., Zhang, C. and Zhou, P. (2021) Influence of the Passive Design of a Building Facade on the Indoor Thermal Comfort of Residential Buildings. *In*, *E3S Web of Conferences*. EDP Sciences, Vol. 237, 03006.
Wang, X., Xia, L., Bales, C., Zhang, X., Copertaro, B., Pan, S. and Wu, J. (2020) A systematic review of recent air source heat pump (ASHP) systems assisted by solar thermal, photovoltaic and photovoltaic/thermal sources. *Renewable Energy*, **146**(September), 2472-2487.
Watermeyer, R. and Milford, R. (2003) The Use of Performance Based Building Codes to Attain Sustainable Housing Objectives: The South African Approach. *In*, *Global Policy Summit on the Role of Performance-Based Building Regulations in Addressing Societal Expectations, International Policy, and Local Needs, Washington, DC USA*, National Acadamy of Sciences, 1-14.
Wells, L., Rismanchi, B. and Aye, L. (2018) A review of Net Zero Energy Buildings with reflections on the Australian context. *Energy and Buildings*, **158**(January), 616-628.
Williams, M. and Moser, T. (2019) The art of coding and thematic exploration in qualitative research. *International Management Review*, **15**(1), 45-55.
World Commission on Environment and Development (1987) *Our common future*. Oxford: Oxford University Press.
World Economic Forum (2019) *Making affordable housing a reality in cities*. Cologny, Switzerland: Company Report.
World Green Building Council (2023) *Sustainable and affordable housing: Spotlighting action from across the World Green Building Council Network*. London, England: Company Report.
Wu, W. and Skye, H.M. (2021) Residential net-zero energy buildings: Review and perspective. *Renewable and Sustainable Energy Reviews*, **142**(May), 110859.
Yamchi, H.B., Shahsavari, H., Kalantari, N.T., Safari, A. and Farrokhifar, M. (2019) A cost-efficient application of different battery energy storage technologies in

microgrids considering load uncertainty. *Journal of Energy Storage*, **22**(April), 17-26.
Yin, R.K. (2006) Mixed methods research: Are the methods genuinely intergrated or merely parallel. *Research in Schools*, **13**(1), 41-47.
Yin, R.K. (2015) *Qualitative research from start to finish*. New York, United States: Guilford publications.
Yin, R.K. (2018) *Case study research and applications - Desing and methods*. 6 ed. London, United Kingdom: Sage.
Zavadskas, E.K., Cavallaro, F., Podvezko, V., Ubarte, I. and Kaklauskas, A. (2017) MCDM assessment of a healthy and safe built environment according to sustainable development principles: A practical neighborhood approach in Vilnius. *Sustainability*, **9**(5), 702.
Zeb, A., de Andrade Romero, M., Baiguskarov, D., Aitbayev, S. and Strelets, K. (2016) LED lightbulbs as a source of electricity saving in buildings. *In*, *MATEC Web of Conferences*. EDP Sciences, Vol. 73, 02004.
Zhang, H., Yang, D., Tam, V.W., Tao, Y., Zhang, G., Setunge, S. and Shi, L. (2021) A critical review of combined natural ventilation techniques in sustainable buildings. *Renewable and Sustainable Energy Reviews*, **141**(May), 110795.
Zhang, S., Yang, X., Jiang, Y. and Wei, Q. (2010) Comparative analysis of energy use in China building sector: current status, existing problems and solutions. *Frontiers of Energy and Power Engineering in China*, **4**(January), 2-21.
Zhang, X.Q. (2016) The trends, promises and challenges of urbanisation in the world. *Habitat International*, **54**(May), 241-252.
Zheng, J., Gao, D.W. and Lin, L. (2013) Smart meters in smart grid: An overview. *In*, *2013 IEEE Green Technologies Conference (GreenTech)*. IEEE, 57-64.
Zuo, J. and Zhao, Z.-Y. (2014) Green building research–current status and future agenda: A review. *Renewable and Sustainable Energy Reviews*, **30**(February), 271-281.

APPENDICES

Appendix A: Questionnaire

Interview Questions

1 - General Questions

1) To set an affordable baseline understanding – What is your view of affordable housing/ How would you classify affordable housing within the context of South Africa?
2) Do you have a common affordable net-zero energy housing design, if not what type of design do you use to reduce the operational energy use of a house?
3) Why did you selected the 'mentioned' housing design?
4) What types of software/programs do you use to model and/or measure the energy efficiency of your designs/projects?
   a) Do these models enhance your ability to design and construct affordable net-zero energy housing?
5) What rating tools have you use to measure your developed housing's sustainability level and why?
6) Can you provide examples of building materials and construction practices commonly used in affordable net-zero energy housing projects?
   a) Which elements did you find help reduce the cost of delivering an affordable net-zero energy house?
7) Do your suppliers, company partners, consultants and contractors promote affordable net-zero energy housing practices?
8) What are some of the challenges you faced when adopting affordable net-zero energy housing designs, initiatives or techniques?
   a) What obstacles currently hinder/prevent the adoption of affordable net-zero energy developments & practices?
9) Are there any potential unintended economic/environmental/social consequences associated with the development of affordable net-zero energy housing, and if so, how can they be mitigated?

2 - Impact on Economic Sustainability

1) Tell me about the type of energy efficient technologies or passive designs you feel are the most practical and beneficial?
   a) Which efficient technologies/passive design have reduced/saved the most energy?
2) How has the adoption of energy efficient techniques and methods impacted your ability to construct/operative/ability to sell the house?
   a) Has the adoption of affordable net-zero energy housing positively impacted the tenant/ purchaser?

3) Has the adoption of affordable net-zero energy housing projects unlocked alternative financing streams to support your developments, if so, to what extent has this improve the viability of your projects?

3 - Impact on Environmental Sustainability

1) Do you focus on the embodied carbon when designing an affordable net-zero energy house?
    a) If yes - How has the development of affordable net-zero energy housing reduce the embodied carbon footprint?
2) To what level does the development of affordable net-zero energy housing promote energy efficiency and conservation of resources?
3) What are the main building elements that will reduce operational energy demanded the most?
4) What role does solar power, wind power, or other renewable energy sources play in net-zero energy affordable housing projects?

4 - Impact on Social Sustainability

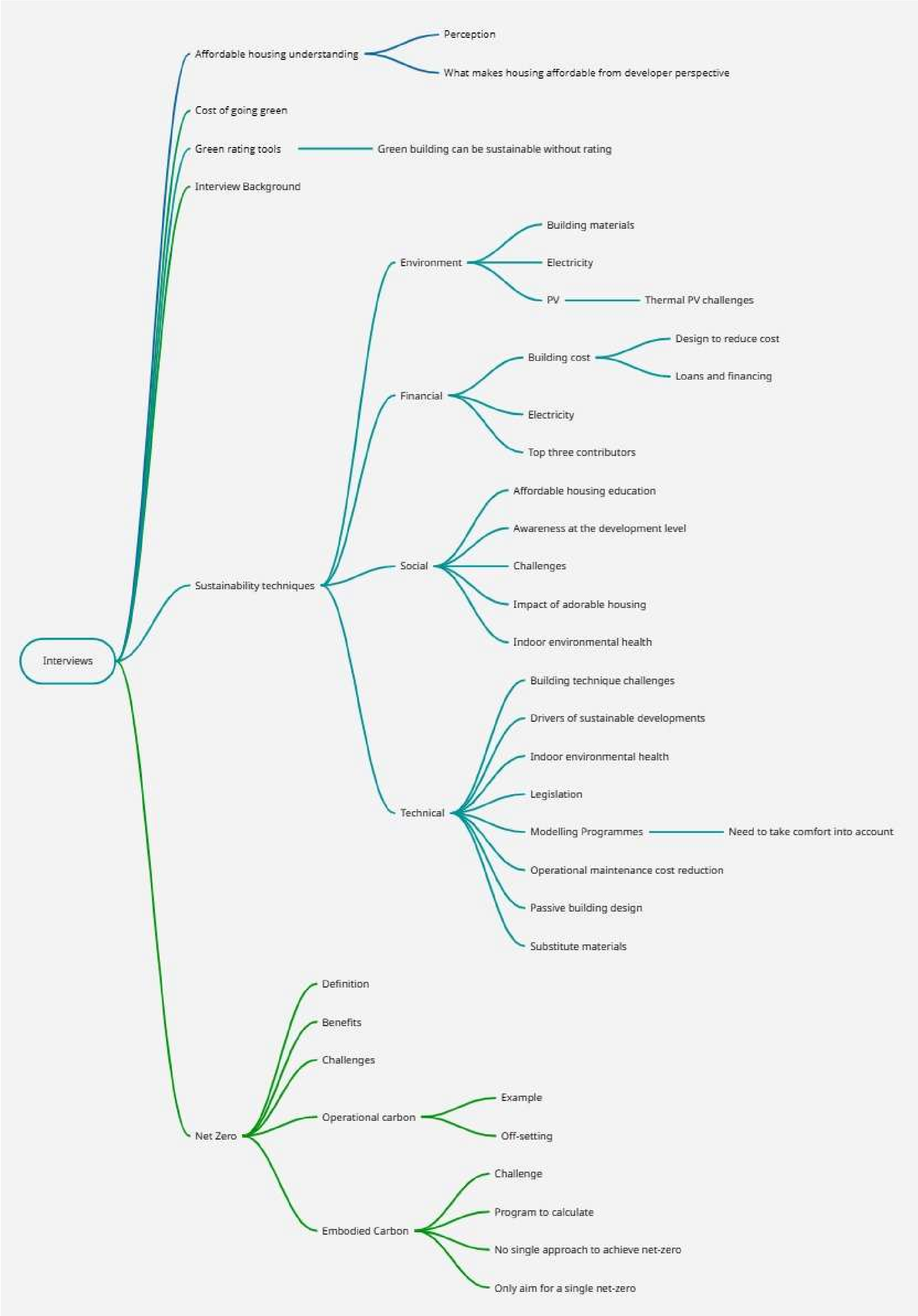
1) Do you engage with clients/purchasers during the planning, construction, and/or management of affordable net-zero energy housing projects?
2) Has the development of affordable net-zero energy housing helped educate your client base?
3) What are the potential social benefits for vulnerable populations, such as low-income individuals, families, or seniors, in having access to affordable net-zero energy housing?
4) Can you discuss any challenges or barriers to achieving positive social impact through affordable net-zero energy housing, and how can they be addressed?
5) Considering the potential of net-zero energy households to alleviate financial stress on low income earners and grid demanded energy. Do you agree that if a building is affordable and net-zero energy, it will enhance South Africa's housing industry and promote economic growth?
    a) What impact do you believe affordable net-zero energy housing will have on South Africa's macro-economic climate?

Appendix B: NVivo Tree Node Structure

Name	Files	References
1. Affordable Housing Understanding	4	5
a. Perception	3	4
b. What makes housing affordable from developer perspective	1	3
2. Cost of Going Green	2	2
3. Green Rating Tools	3	5
a. Green building can be sustainable without rating	1	1
4. Interview Background	3	3
5. Net Zero	2	2
a. Benefits	1	1
b. Challenge	2	8
c. Definition	1	1
d. Embodied Carbon	3	7
i. Challenge	2	5
ii. Program to Calculate	1	1
iii. No single approach to achieving Net Zero	1	1
iv. Only aim for a single net zero	2	2
e. Operational Carbon	3	7
i. Example	2	2
ii. Off-setting	2	2
6. Sustainability Techniques	1	1
a. Environment	1	1
i. Building Materials	1	1
ii. Electricity	3	7
iii. PV	2	2
• Thermal PV Challenges	1	1
iv. Water	1	1
b. Financial	1	4
i. Building Cost	2	8

• Design to reduce cost	1	4
• Loans and Financing	3	5
ii. Electricity	2	3
iii. Top three contributors	2	2
c. Social	0	0
i. Affordable Housing Education	2	3
ii. Awareness at the Development Level	3	9
iii. Challenges	3	8
iv. Impact of affordable housing	2	2
v. Indoor Environmental Health	2	2
d. Technical	0	0
i. Building Technique Challenges	2	7
ii. Drivers of sustainable developments	1	2
iii. Indoor Environmental Health	1	1
iv. Legislation	4	9
v. Modelling Programmes	3	5
• Need to take comfort into account	1	1
vi. Operational Maintenance Cost Reduction	1	1
vii. Passive Building Design	3	5
viii. Substitute Materials	2	4

Appendix C: NVivo Tree Node Map



Appendix D: Ethics Clearance

UNIVERSITY OF CAPE TOWN
IYUNIVESITHI YASEKAPA • UNIVERSITEIT VAN KAAPSTAD

2023/09/28

EBE/00439/2023

RE: Research Ethics Committee Project Approval Letter

Dear Dylan Hübner,

Your application for ethics review of your project titled

Evaluating the Sustainability Impact of Affordable Net-zero Energy House within South Africa

has been reviewed and evaluated by the

Engineering & Built Environment Committee.

You may proceed with your research project titled:

Evaluating the Sustainability Impact of Affordable Net-zero Energy House within South Africa

Please note that should:

(i) any serious or adverse effects to participants occur and/or,

(ii) aspect(s) of your current project change and/or

(iii) any unforeseen events that might affect continued ethical acceptability of the project occur then you should immediately report this to the approving REC. You may be required to submit an amendment to this application, in order to determine whether the changed aspects increase the ethical risks of your project.

Based on the information supplied your application has been successful and is approved.

Please note the following additional conditions associated with this approval:

(i)

Regards,

Engineering & Built Environment Committee.

Appendix E: Consent Form

UNIVERSITY OF CAPE TOWN
IYUNIVESITHI YASEKAPA • UNIVERSITEIT VAN KAAPSTAD

Dylan Hübner (Mphil Candidate)
University of Cape Town
Room 5.08, Fifth Level
Snape Building, Engineering Mall
Upper Campus
Rondebosch 7701,
Cape Town
Cell: +27 76 150 5156
Email:
HBNDYL001@myuct.ac.za

Consent Form

To whom it may concern,

Title of research project: Evaluating the Sustainability Impact of Affordable Net-zero Energy House Within South Africa

Name and position of the researcher: Dylan Hübner, Mphil candidate, Construction Economics & Management, University of Cape Town

You are invited to participate in an affordable housing research study conducted by Mphil student Dylan Hübner. The research will be supervised by Associate Professor Kathy Michell of the University of Cape Town and Dr Alireza Moghayedi of the University of West England. The dissertation's results will be presented to the department of Construction Economics and Management in fulfilment of the requirement for the completion of the degree of Master of Philosophy in Construction Economics & Management.

If you have any queries regarding the research, please feel free to contact the student or supervisor.

Student contact details:
Dylan Hübner - 076 150 5156 - HBNDYL001@myuct.ac.za

Supervisor contact details:
Dr Alireza Moghayedi - Alireza.Moghayedi@uwe.ac.uk
Prof. Kathy Michell - kathy.michell@uct.ac.za

Purpose of the Study
The primary objectives of this research are to:

- Identify and analyse the critical success factor mechanisms that form the foundation of an affordable net-zero energy house.
- Determine the construction, material, technology and building technique factors that must be considered in achieving affordable net-zero energy houses.
- Evaluate the state and potential influence of the affordable net-zero energy houses on South Africa's lifecycle emissions.
- Access the impact of affordable net-zero energy houses on both the lifecycle costs of affordable housing and their environmental effect on CO2 emissions.

This study aims to ascertain the nature, degree, and benefits introduced by affordable net-zero energy housing and its impact on the lifecycle sustainability of affordable housing in South Africa.

Procedures
Your participation in this study is voluntary and should you volunteer to participate in this study, please advise me as to the time and place that would be suitable for an interview to be conducted. Should you wish to withdraw from the research or refuse to answer any questions you may do so without any consequences. Additionally, secondary supplementary data will also be collected to further substantiate the interview.

Potential Benefits to the Participant
The findings will be shared with you upon the completion of the dissertation.
The findings in this dissertation may be applicable to your company and may help with generating more informed decisions regarding the implementation of affordable net-zero energy housing.

Confidentiality
All information will remain confidential, participant names (Optional) and company names (Optional) will be addressed as A, B, C etc. and 1, 2, 3 etc, respectfully. A copy of the questionnaire/ interview recordings/ supplementary data will be provided free of charge on request by the participants or their company with permission from the participant in question. Collected data will be processed manually and with the use of software (eg: NVivo) where necessary. Upon submission of the dissertation all recorded information and statistics will be destroyed and erased.

Rights of Research Participant
Your participation during the interview may be terminated at any time during the answering of the questions in the interview. Your consent preceding the interview may be revoked with no consequences and all your information and shared statistics will be terminated immediately.

Interview Procedure
Interviews may be conducted either online or face-to-face at your discretion. Furthermore, you may choose your preferred online medium for the interview. In the case of face-to-face meetings, you may choose your preferred physical location to meet with the researcher. Moreover, interview sessions will be an hour long to ensure an adequate amount of time will be allocated to the interview.

Please indicate below by ticking the appropriate box your preferred method by which the interview will be conducted:

- ☐ Face-to-face meeting
- ☐ Online meeting

Signature of Research Participant
I confirm that I have read and understood the information the researcher is seeking for in the study of

> *"Evaluating the Sustainability Impact of Affordable Net-zero Energy House Within South Africa"*

I acknowledge that my participation is voluntary and I may withdraw from the study at any time without providing a reason.
I have been provided with a copy of this form as a point of reference.
My questions have been answered to my satisfaction and I fully consent to participate in this study.

Name of Participant:

___

Company of Participant:

___

Date:

___

Signature:

___