



**APPRAISAL AND OPTIMIZATION OF ENERGY-EFFICIENT GREEN BUILDINGS IN  
SOUTH AFRICA**

**BY**

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## ABSTRACT

Generally, over 35% of global energy use and 40% of carbon emissions are attributed to the built environment while future forecasts indicate that these values may rise much further. In South Africa (SA), building stocks account for 40% of the country's final energy demand which strains the country's coal-dependent energy grid and oftentimes results in power outages. Optimizing energy efficiency and thermal comfort while attaining the lofty goal of carbon neutrality is essential for all concerned stakeholders in the building sector globally. Meanwhile, green building (GB), being a recognized revolutionary theory and practice in the building industry, is suggested as a solution to SA's environmental challenges. On this wise, this research aimed to develop energy-efficient models for optimizing green buildings into the design and operation of buildings to allay their environmental impacts. The goal was to enhance energy efficiency, decrease energy consumption, and mitigate carbon emissions across diverse climates, thus benefiting South Africa's built environment. To achieve the study's goals, three primary research objectives were identified and pursued namely: (i) To provide an overview on status-quo of green building development in South Africa with a view to explore the status quo and provide roadmap for improvement; (ii) To examine the energy-saving potential of incorporating building-integrated greenery systems towards climate-resilience in the subtropical climate zone of South Africa; and (iii) To investigate the energy-performance of green building renewable energy utilization systems within South Africa's hot and arid climate zones. Initially, the study's first objective entailed a comprehensive literature overview integrating climate, sustainability, and building energy modeling within the South African context. This was carried out through a scoping review approach via the PRISMA guideline of reporting Subsequent objectives involved selecting reference buildings and creating hypothesized models as case studies based on six climate zones from the South African National Standard. For the second objective, a thorough and integrative approach that linked building energy modelling and varying climatic change was devised. The numerical parametric simulation and analysis, being a quantitative research approach was adopted as a data collection method. Similarly, the third objective employed numerical parametric simulation as a data gathering method in this research, which is based on a quantitative analysis to explore various design options iteratively. In the second and third objectives, Global climate databases, Meteonorm, Climate Consultant, and energy simulation software such as DesignBuilder, EnergyPlus, and Polysun were used for weather data analysis, climate modeling, and building energy simulation. The findings highlighted that while South Africa boasts notable green construction projects, scientific research progress has not matched international levels. The focus was on promoting green building adoption through standards, certifications, and incentives. However, gaps

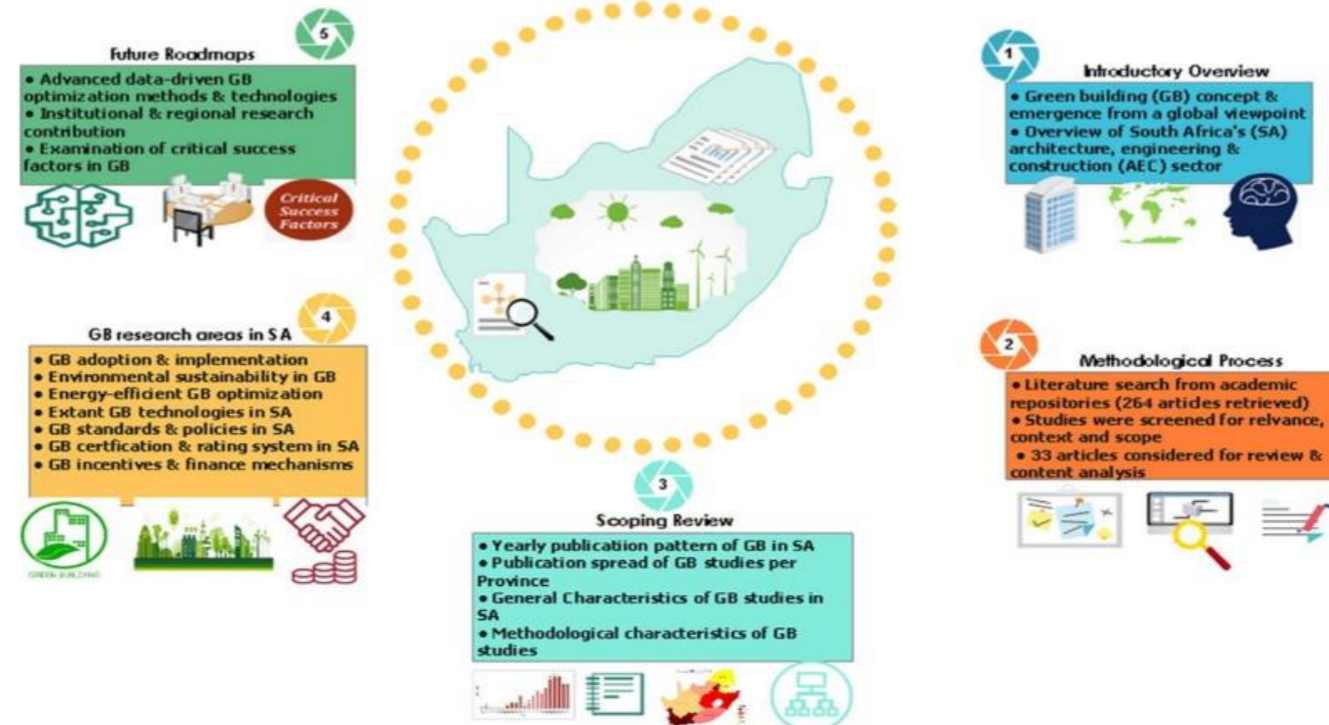
were observed in optimized energy performance and post-occupancy evaluation of existing buildings. Despite high awareness, the utilization of green building technologies among South African professionals did not meet anticipated levels. For the second objective, the study's findings indicated an increase in extreme heat waves with higher peak temperatures in the future. Building energy use in the study area is projected to rise by 8-24% from 2030 to 2080. Notably, heat gains primarily result from envelope thermal transfer rather than solar radiation. Greenery systems were found to effectively support green building goals and urban sustainability across anticipated seasons. Nature-based solutions proved successful in adapting to climate change compared to non-retrofitted conventional buildings. For the last objective, the study revealed regions with substantial solar irradiance, indicating potential for renewable energy adoption. It emphasized the need for durable BIPV systems in high-temperature conditions. BIPV modules generated more energy in Upington than Nelspruit due to varying solar radiation. Opportunities were identified for BIPV systems to achieve optimal power generation. The study provides a foundation for informed decision-making, policy formulation, and targeted research in sustainable building practices. The study presents practical principles to guide urban planners and policymakers in integrating eco-friendly technology into both new and existing building designs. This promotes sustainable urban development and reduces cities' carbon emissions. Going forward, to showcase the effectiveness of these energy-efficient and climate-responsive systems to the public and industry stakeholders, it is recommended to establish and enhance large-scale demonstration projects in South Africa's subtropical, hot and arid regions.

**Keywords:** Green building, energy efficiency, BIPV, climate change, greenery systems, South Africa

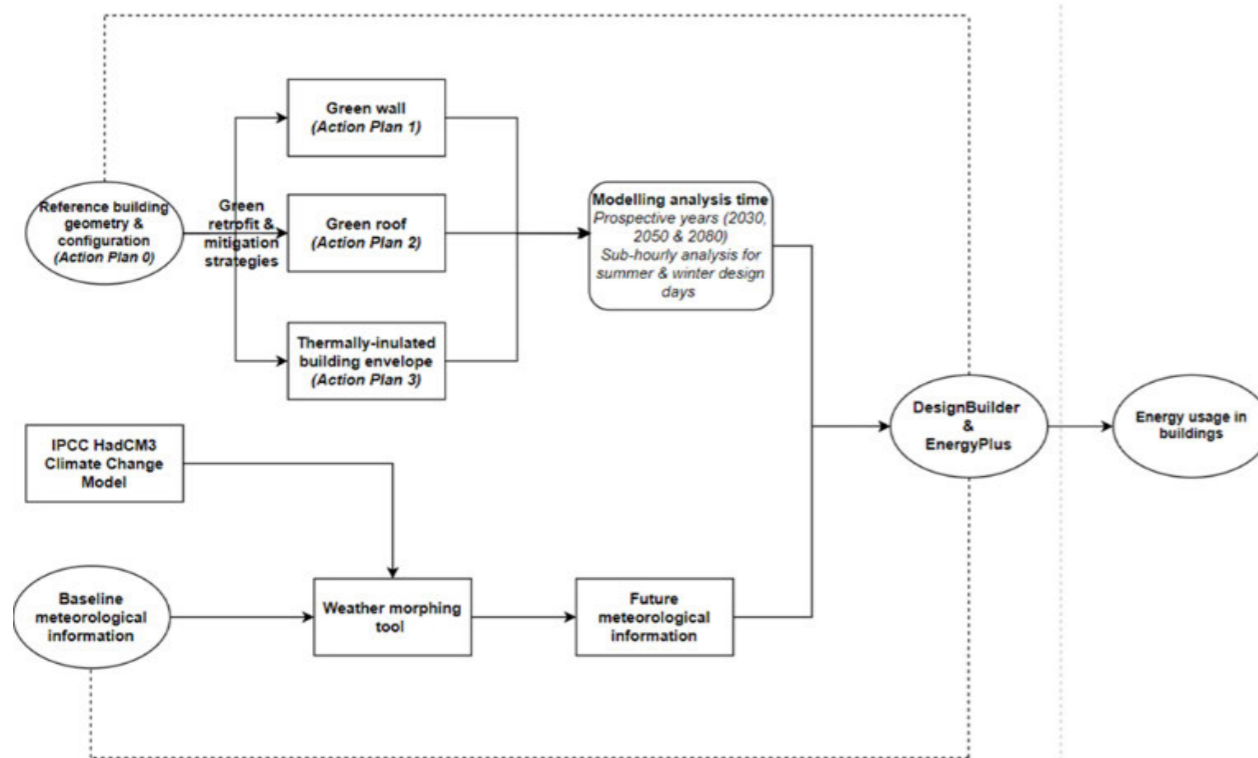
# GRAPHICAL ABSTRACT

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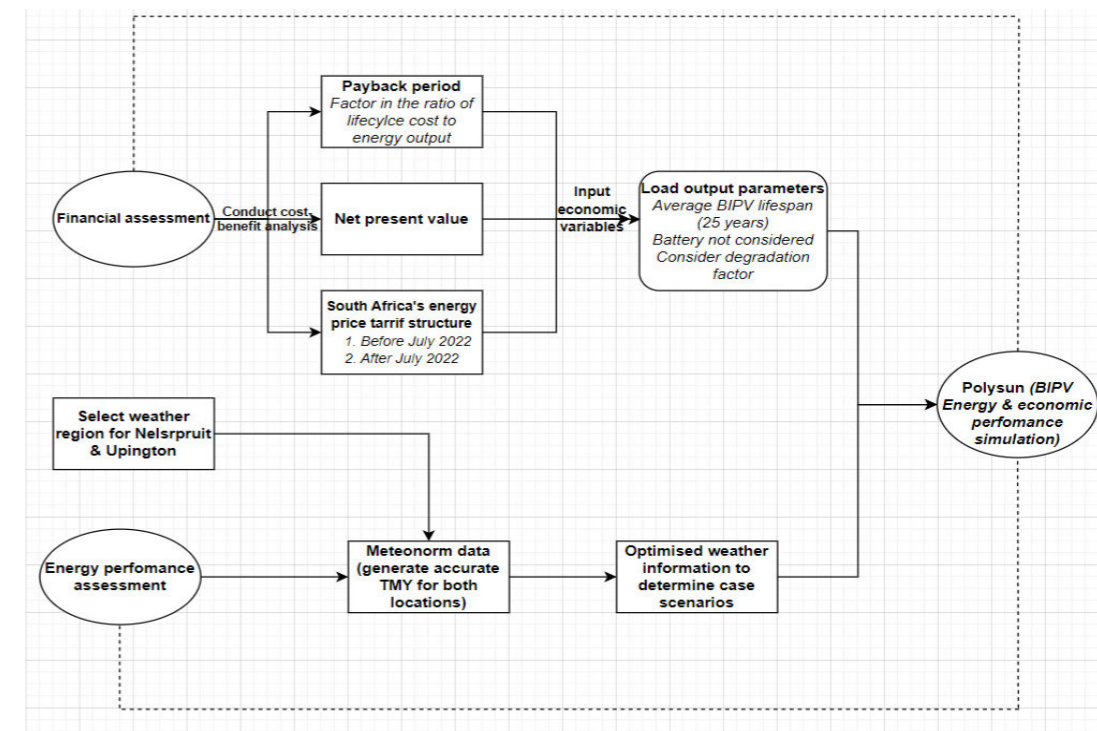
## Green Building in South Africa



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## APPRAISAL AND OPTIMIZATION OF ENERGY-EFFICIENT GREEN BUILDINGS IN SOUTH AFRICA

# DECLARATION

I, **FAVOUR DAVID AGBAJOR**, certify that this dissertation's intellectual content is entirely the result of my effort, except for the references and bibliographies cited. This research work, in whole or in part, has never been submitted to any other university for review, publication, or any other purpose.

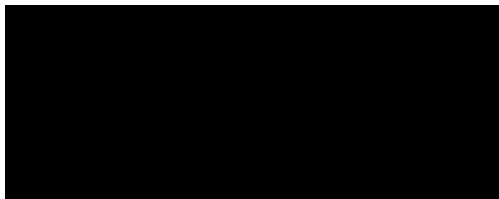
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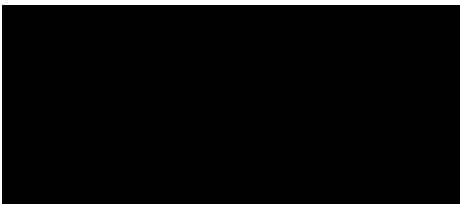


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for

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20.09.2023

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**Date**

## **DEDICATION**

This dissertation is dedicated to God; the Supreme Construction Manager who created the entire universe and suspended it in the space. He has assuredly been my wellspring of knowledge, wisdom, strength, and creative vigour throughout the period of this academic research rigour. This work is also dedicated to my pious parents and sterling siblings for their courteous concern, lively luminous love, substantial support and profound prayers during the programme.

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# LIST OF PUBLICATIONS

Chapters of this thesis have been fully or partially published in the following publications:

## **Refereed Journals (*Published*)**

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## **LIST OF ABBREVIATIONS**

AEC: Architecture, Engineering and Construction

ANN: Artificial Neural Network

BIM: Building Information Modelling

BIPV: Building Integrated Photovoltaic

EPC: Energy Performance Certificate

GB: Green Building

GBRS: Green Building Rating Systems

IEA: International Energy Agency

IoT: Internet of Things

ML: Machine Learning

LCA: Lifecycle Assessment

LEED: Leadership in Energy and Environmental Design

RBT: Robotics

SANS: South African National Standard

# CHAPTER 1

## Introduction

### 1.1 Chapter Overview

The background and motivation of the study is presented and discussed in this chapter, along with the problem statement that led to the research aim, objectives and study scope. Additionally, it provides a brief on the various research methodologies used alongside the study's significance and outcomes. Lastly, the thesis structure is presented in this chapter to make it easier to get through the chapters.

### 1.2 Study's Background and Motivation

By and large, there is a constant and exponential pace of utilization of resources on the universe since its resources are finite coupled with its constrained capacity to regenerate itself (Zhang *et al.* 2023b). The 21<sup>st</sup> century greatest ecological hazard is seen in natural resources' depletion and the acceleration of climate change emanating from the unsustainable use of resources and energy alongside the hiking necessity for raw materials (Jin *et al.* 2022). Typically, the dire consequence on nature is evident in declining natural vegetation, urban heat island, aquatic habitat extinction and such like. For the built environment in specifics, each phase of the building lifecycle (that is, from construction to demolition) is resource-consuming and energy intensive, making the world's building sector responsible for 40%, 25% and 18% of energy and resource consumption, global deforestation, and surface water drawdowns respectively (Zuo and Zhao 2014; Marotta, Porrás-Amores and Rodríguez Sánchez 2023)

As a result, the idea of sustainable development has been advocated as such a one that propels the utilization of world's resources for human growth while ensuring the sustainability of the natural systems that reinforce the provision of natural resources and ecological functions (Olawumi and Chan 2018). The sustainable development practice, which comprises employing the ideal pragmatic approaches along with safe, serene and resource-efficient techniques to produce constructed edifices or structures from raw material extraction to the demolition and disposal of their components, is applicably exhibited in the architecture, engineering, and construction (AEC) sector by green building and/or green building projects. In other words, infrastructural development in the AEC's sector in this current era is globally governed by the green building philosophy, evolution, advanced initiatives, and whatnot (Agbajor and Mewomo 2024).

Promisingly, green construction initiatives provide a considerable significance to the AEC sector's sustainable growth with core contribution to the threefold elements of sustainability – social (people),

economic (profit) and environment (planet). From the social viewpoint, green construction initiatives have granted improved solace, comfort and wellbeing to building occupants (Devine and McCollum 2019). As opined by Zitars *et al.* (2021), green building initiatives from environmental outlook have an infinitesimal instant effect on the natural world and ecosystem in general. Meanwhile, Yan *et al.* (2022) argued that the intertwined economic benefits of green building initiatives comprise increased demand, financial feasibility, and profits. To this end, there abounds an intense accentuation regarding the green building subject vis-à-vis its management and delivery by AEC industry stakeholders. For instance, many developed climes or Global North countries like Singapore, Australia, Hong Kong and the United States of America (USA) are ahead of the curve in green building design, construction, delivery and operation. According to statistics from the literature, the green floor area or green space accounts for US\$87.5 billion, US\$83 billion and US\$25.4 billion in Singapore, USA and the United Kingdom respectively (García Sánchez, Solecki and Ribalaygua Batalla 2018; Basu and Nagendra 2021). Likewise, emerging economies or Global South regions like Brazil, South Africa, Vietnam, among others, are making giant strides to the production of green construction projects (Nguyen *et al.* 2017; Zepeda-Gil and Natarajan 2020; Agbajor and Mewomo 2022b).

In a different standpoint, prominent researchers have been engaged in a plethora of studies regarding green building development in past decades. While there are varied definitions for green building, it can be referred to as a healthy and eco-friendly building that utilizes efficiently used resources for its design and construction (Pan, Yu and Du 2022). Additionally, Rameshwar *et al.* (2020) described it as “the formation of effective building element and the adoption of proper processes that are eco-friendly and resource-efficient within each phase of building lifecycle” and it tends to practically make up for such energy inefficiency issues that surrounds most common buildings (Uddin *et al.* 2018). Overall, green building helps in reducing environmental threats posed by the built environment and seeks to provide a healthy nexus between humans and nature (Wuni, Shen and Osei-Kyei 2019; Li *et al.* 2020). The main domains in green building research as identified by Ahmad, Aibinu and Stephan (2019) include benefits, drivers, barriers, risks, critical success factors and project delivery attributes the which serves as a bedrock for further studies. Meanwhile, as digital revolution continues to address complicated difficulties in diverse worldwide sectors, it has a positive impact on the built-environment industry (Agbajor and Mewomo 2022a). Thus, innovative digital technologies such as building information modeling (BIM), artificial intelligence (AI), machine learning, internet of things (IoT), blockchain technology, virtual reality, augmented reality, and such like have really been advocated for by a number of academics (Darko *et al.* 2019).

Nonetheless, the knowledge and provision of ample solutions to the wholesome complexities

encircling green building from cradle to credence has been challenging. More specifically, issues within the spectrum of zero-carbon buildings like design iteration, energy modelling, energy efficiency, enhanced simulation and optimization, sensitivity analysis and validation, energy performance evaluation, green building certification schemes and whatnot, which are imperative for producing and maintaining sustainable buildings require needful consideration (Darko and Chan 2016). Furthermore, to enhance the effectiveness and eco-friendliness of green building energy management, (Zheng, Kamruzzaman and Jinyao 2022) stressed the need for novel digital services and analytics, oftentimes requiring the joint inputs of multifaceted practitioners in a synergistic and interconnected way. Likewise, since the design and development of green buildings requires modern technologies and materials, this makes the overall process a sophisticated one, thus influencing its delivery and operation. For example, renewable energy technologies like solar, geothermal and wind energy that can improve the energy-saving and performance efficiency of green buildings are oftentimes climate-dependent and region specific (Lai *et al.* 2023) while new materials like eco-block, phase change materials, geopolymers concrete, and such like, which can enhance thermal comfort requires adequate design and construction expertise (Oyerinde *et al.* 2023; Agbajor and Mewomo 2024).

To actualize the overarching goal of producing and maintaining carbon-neutral and climate-resilient structures, the optimization of energy efficiency in ecofriendly buildings is deemed essential while ensuring users wellbeing as they constitute the chief dwellers of green buildings (Li *et al.* 2021a). An awareness of energy efficiency by building occupants needs to be considered by stakeholders in green construction projects, particularly at the design and operation phase. According to Mustaffa and Kudus (2022), pragmatic commitments by practitioners at a larger scale can produce better implementation of high-performance buildings, considering the growing crucial concerns to abate the building energy use and decarbonize the AEC sector globally.

Stimulated by the aforesaid narrative, this study strives to produce a substantial contribution to extant works on green building development with reference to South Africa's built environment and climate by developing energy-efficient models for the operational stage of building lifecycle. Consequently, this study becomes important to policymakers, building designers and constructors in determining initial models for energy-efficient green building, thus helping them to implement a wholesome practice in the entire life of a building.

### **1.3 Problem Statement**

The rising trend in global economy has birthed a tectonic shift among the first world cities and developing nations, thereby shaping human livelihood all over the universe. The increasing influx of

human beings into buildings and cities as modern society moves toward urbanization have created unusual difficulties. Projections revealed the global population to reach nearly 8.5 billion and 9.3 billion people by 2030 and 2050 respectively with 60% and 68% of the populace living in urban areas (Zhang 2008). Meanwhile, sub-Saharan Africa is recognized as the fastest urbanizing region in the world (Saghir and Santoro 2018). However, this exponential urban growth in sub-Saharan Africa might pose serious issues in attaining sustainable cities and societies, affordable and clean energy, good health, and well-being, which are relevant to the built environment.

Buildings that are energy-efficient and sustainable are essential on a worldwide scale, especially in the world's rapidly growing nations like South Africa. Conversely, Agbajor *et al.* (2023) mentioned that 40% of South Africa's final energy use is accounted for by the building industry, which strains the country's coal-dependent energy supply grid and often causes power outages. Based on reports by the International Energy Agency (IEA 2021), the nation experienced substantial declines in energy efficiency between 2010 and 2014 due to economic growth, urban sprawl, increasing housing stock and electrification in the countryside. Thus, the price tariff and demand profile for energy reached their peak in 2021. In 2022, the Annual State of Climate reported by the South African Weather Service (SAWS) highlighted several ecological hazards in selected locations across all provinces in the country (SAWS 2022). This ranged from excessive rainfall and flooding to rising water levels that claimed lives and caused sudden homelessness among individuals in almost all provinces. Moreover, severe thunderstorms and various veld fires were reported to ripped parts of Northern Cape and Western Cape respectively. Furthermore, the greenhouse gas emissions from ineffectual energy use by buildings is closely linked to the dire effects of climate change in the nation. Likewise, data from SAWS described that despite above-average rainfall, 2022 is the fourth-hottest year (41.7°C in Upington, Northern Cape) ever recorded for South Africa (SAWS 2022).

With the sole aim of minimizing the impacts that the built-environment sector has on natural environment, continual emphasis is made on sustainable development with key policies being enacted by the South African government. Similarly, several research efforts have been done in South Africa from the context of green building adoption and practice. The studies conducted by (Windapo 2014) and (Masia, Kajimo-Shakantu and Opawole 2020) identified, established, and determined the drivers, benefits and barriers to implementing key green building principles and technologies in South Africa. Although these studies created awareness regarding green building adoption, only a very few studies have addressed how green building can be optimized with regards to urban growth in the country.

Moreover, the research of Oguntona *et al.* (2019b) identified the drawbacks to energy-efficient building retrofit. In the meantime, Xia, Zhang and Cass (2012) examined the energy management

practices of commercial buildings, while Fan and Xia (2018) proposed a methodical building retrofit strategy that considered both indoor and outdoor systems. While these extant studies have gainfully addressed issues regarding green building from an energy management outlook, none have explored the performance of greenery systems as energy saving measures for buildings in relation to the present and prospective climate change. Globally, our greatest issue today is tackling climate change, which is made more difficult by the fact that existing buildings present a major obstacle.

Promisingly, the world consents that green buildings provide hopeful answers to address this grave climate problem (Azis 2021) and South Africa is no exception. Therefore, this study seeks to explore some proven pragmatic actions that can encourage sustainable development and accelerate the transition towards a green built environment in South Africa as the country seriously seeks to achieve its carbon neutrality goal by 2050. Since energy efficiency is a vital objective of green building initiative, its performance in buildings and ecological impact will prove beneficial to the country's built-environment sector.

#### **1.4 Research Aim, Objectives and Scope**

This research is aimed at providing means of improving energy efficiency in buildings by developing an energy-efficient model for green building optimization towards a reduced energy consumption and carbon emission of these buildings under varying climatic conditions to attain environmental benefits in urban centres.

The specific objectives of this study are to:

1. To provide an overview on status-quo of green building development in South Africa with a view to explore the status quo and provide roadmap for improvement.
2. To examine the energy-saving potential of incorporating building-integrated greenery systems towards climate-resilience in the subtropical climate zone of South Africa.
3. To investigate the energy-performance of green building renewable energy utilization systems within South Africa's hot and arid climate zones.

The study's scope focused on enhancing energy efficiency in building envelopes with respect to climate change. The first objective entailed a holistic literature overview for an immersive understanding of the current trend of green building. Other research objectives involved investigative analysis on the current and future benefits of embracing nature-based and renewable energy measures for green building development under three varying climate conditions in South Africa. Specifically, Objective 2 deals with the greenery-based energy-saving systems comprising green walls, green roof

and thermally-insulated green envelope materials as climate change mitigation measures for existing buildings. This objective focused on Durban – a subtropical climate city in South Africa. Objectives 3 and 4 entails the improved energy performance and economic viability of building-integrated renewable energy systems in two climatic regions of South Africa. In specifics, the objectives focused on the building-integrated photovoltaic (BIPV) system, being a renewable (solar) energy technology abundant in the cities of Upington (an arid climate zone) and Nelspruit (a hot interior climate zone).

### **1.5 Research Methodology in Brief**

Research methodology simply refers to the underlying theory of a research study and the rationale behind its design. It is a combination of techniques used to enquire into a specific reality and how observations about such reality are analysed and disseminated (Kumar 2018). The research approach may be either qualitative, quantitative or mixed. This study employed both research approaches because it entails simulating and forecasting the performance of building systems using numerical methods, algorithms, and mathematical equations (Bamdad *et al.* 2021). Initially, the first objective in this study involved a comprehensive and systematic review of extant literature. Since this study involved an integrated blend of climate, sustainability and building energy modelling, it was important to undertake an in-depth literature overview on green building research and practice within South African climate. For other objectives, some reference buildings were selected and hypothesized building models were developed as case studies. These were facilitated using the six climate zones in South Africa as per the South African National Standard (SANS 10400 Part XA). The research employed parametric design analysis to methodically investigate design options by iteratively testing a variety of combined design parameters of buildings. Moreover, weather data were obtained from prominent global databases (such as [climate.onebuilding.org](http://climate.onebuilding.org) and International Weather for Energy Calculation) and were analysed using climate models like Meteonorm and Climate Consultant. Energy simulation software including DesignBuilder, EnergyPlus, Polysun were utilized for building energy modelling, simulation and parametric analysis.

### **1.6 Research Significance and Outcomes**

Developing an exact energy-efficient models for green building has a crucial impact especially at the inception phase of residential buildings lifecycle. Neglecting to adopt climate-responsive and energy-efficient measures in building planning, design and construction might result in structures that demand much energy to run the building services thus posing over-reliance on national grids and non-renewable fossil fuels.

Hence, the findings of the study will be of great importance to building designers and constructors in determining initial models for energy-efficient green buildings, thus helping them to implement a wholesome green building practice in the entire life of a building. More so, the findings of the study will aid clients, real estate owners in augmenting this development into their future building plans since they are the most users of buildings. To the academic community, the results will contribute more to existing knowledge corpus regarding energy efficient green buildings and create avenues for further research trends either theoretically or experimentally. Lastly, it will also help the governments in enhancing green building plans, policies, and such like.

The following outcomes are highlighted below:

- 1) Annual energy saving potentials that will integrate electrical, thermal and cooling energy for building applications will be analysed
- 2) Improved outcomes in sustainable energy-efficient buildings and reduction in energy consumption, carbon emissions.

### 1.7 Ethical Consideration

The study was conducted with no ethical problems and ensured no risk to humans, animals and environment All surveys and information gathered were handled discreetly and kept confidential. After in-depth evaluation, the Institutional Ethics and Research Committee provided ethical clearance, upon request, and the research was conducted in conformity with the university's ethical standards.

### 1.8 Structure of the Thesis

Table 1.1 outlines the work presented in each chapter of this thesis

**Table1.1:** Study’s synopsis described in each chapter

CHAPTER	DETAILS
1	<b><u>Introduction</u></b>
2	<b><u>Literature Review</u></b> Review previous studies related to (i) global energy and environment (ii) Climate change and sustainable development; (iii) built environment sector and sustainable construction (iv) an overview on green building (v) strategic energy-efficient measures for green building (vi) optimization approaches for energy efficiency in green building and (vii) Chapter summary.
3	<b><u>Research Methodology</u></b> The chapter served to validate the study's methodology, beginning with the foundational philosophy and rationale. It then outlines the research approach, including design, data collection, and analysis techniques, ensuring the study's objectives are met.

4	<p><b><u>Green Building Research in South Africa: A Scoping Review and Future Roadmaps</u></b>  Presents a systematic review of relevant publications in the body of knowledge to provide an overview of green building roadmap for its enhancement in the construction industry.</p>
5	<p><b><u>Optimized energy-saving potential of building-integrated greenery systems in the subtropical coastal climate of Durban, South Africa</u></b></p> <p>The primary aim of this chapter was to evaluate the potential of green systems in saving energy for buildings in the subtropical coastal climate of southeastern South Africa, within the context of climate change. A building survey selected a representative three-story university building in Durban. Three strategies to mitigate energy demand growth were examined: green walls, green roofs, and thermally insulated green envelope materials. These strategies were evaluated against projected weather conditions for 2030, 2050, and 2080.</p>
6	<p><b><u>Optimized energy-performance of green building-integrated photovoltaic systems (BIPV) in hot and arid regions of South Africa</u></b></p> <p>In this chapter, the focus was on exploring the feasibility and energy-saving capabilities of BIPV (Building Integrated Photovoltaics) systems. The research utilized Nelspruit and Upington as case studies to practically evaluate the implementation of green BIPV systems in South Africa's hot interior and arid interior climate zones.</p>
7	<p><b><u>Conclusions and Recommendations</u></b></p> <p>Concluding this chapter involves summarizing the research's goals, objectives, and findings. It also emphasizes the study's importance, theoretical and practical contributions, while acknowledging limitations and offering relevant suggestions for future research.</p>

## 1.9. Chapter Summary

This chapter have depicted and discussed the study’s backdrop and incitement alongside the research problem that gave rise to the study’s aim, objectives and scope. Also, it presented an overview on the research approaches used along with the study's significance and outcomes. Finally, it illustrated the thesis’s outline to easily navigate other chapters.

# CHAPTER 2

## Literature review<sup>1</sup>

### 2.1 Chapter Overview

This chapter is divided into six major segments to provide a holistic knowledge in relation to the research study. The first part deals with conceptual trend regarding universal energy use and natural environment. In the second part, a conceptual background within the broad spectrum of climate change and sustainable development was discussed. This gave rise to the specific narration of issues surrounding the construction industry and sustainable construction in the third segment. The fourth section discussed a detailed account on green building concept where the current trends of global policies, rating systems, adoption and implementation towards green building development are fully delineated. Also, the section provides insights on the incentive mechanisms that fosters green building promotion and contemporary digital technologies that advances its development. Energy-efficient strategies for green buildings were described in the fifth section. These comprise nature-based and renewable energy measures alongside passive building envelopes. In section six, classical, heuristic and data-driven techniques to optimise energy efficiency in green buildings were demystified.

### 2.2. Global Energy and Environment

In today's world of 4<sup>th</sup> industrial revolution, *energy use* is very central as every person on the earth daily utilizes energy in a plethora of ways. By and large, *energy* is often regarded as the backbone of modern societies and the mainspring of any national economy towards a sustainable future (Amasyali and El-Gohary 2018). Its access, conversion, utilization, management, conservation and whatnot are multidisciplinary in nature and eventually channelled to diverse sectors of global economy (chiefly the industrial, transport and building sectors). The incessant increase in energy demand is not only witnessed in most developed and industrialized climes but also rapidly growing and prevalent by the

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<sup>1</sup> This chapter is largely based upon the following publications:

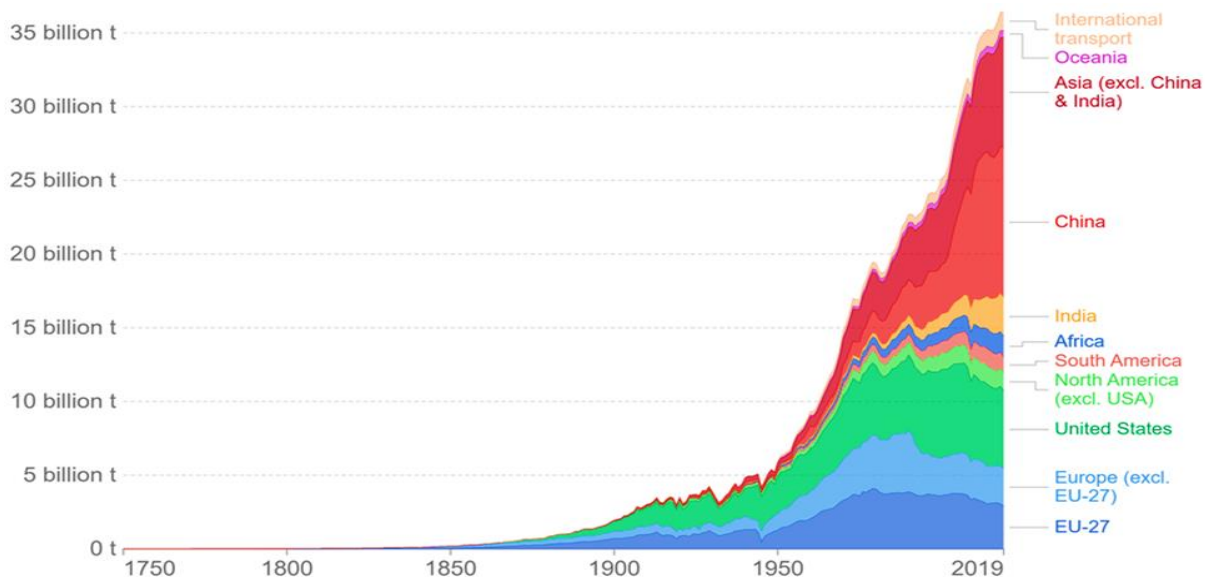
F.D. Agbajor, M.C. Mewomo, V.B. Umoh & S.A. Makanjuola (2023). "Building energy management system research in South Africa – Adecade overview." *Energy Reports 9S10 (2023) 33-39*, <https://doi.org/10.1016/j.egy.2023.05.056>

C.C. Ejidike, M.C. Mewomo, F.D. Agbajor & T.O. Olawumi (2023). "Drivers for building retrofitting practice: A systematic review." In Book: *Building Smart, Resilient and Sustainable Infrastructure in Developing Countries (2023)* pp. 265-272. <https://doi.org/10.1201/9781003325321-28>

F.D. Agbajor & M.C. Mewomo (2022) "A bibliometric review on application of digital technologies in green buildings." In proceedings: *16th Built Environment Conference on Construction in 5D: Deconstruction, digitalization, disruption, disaster, development: A second look*. Association of Schools of Construction in Southern Africa, Lanseria, South Africa, 301-311

global south, especially the emerging economies. This happens in a bid to fulfil human need for such energy-centric services as heating, cooling, cooking, lighting, communication, transportation and such like (Jia *et al.* 2022). Evident statistical report revealed the global energy demand surged by 31EJ in 2021 (Zhou *et al.* 2023). Meanwhile, as the world recovered from the pandemic, the global energy consumption surged in 2022. From a continental outlook, the International World Agency (IEA) reported that the energy consumption in China, Brazil, the United States, South Africa, Australia and Qatar reached 3621 million tonnes of oil equivalent (Mtoe), 312Mtoe, 237Mtoe, 132Mtoe, 128Mtoe and 25Mtoe respectively, accounting for 4.6%, 3.7%, 2.4%, 3.9%, 1.6% and 2.8% in each of the listed region (Citaristi 2022).

What is cause for painstaking concern is that the global community continues to experience energy shortages, ecological hazards, pollution, and climate change as the benefits to the environment have frequently been greatly undermined by incessant upsurge in energy utilization regardless of myriads of notable and impressive high-tech innovations. Consequently, fossil fuel use, in specifics, places a great deal of strain on the ecosystem and harms people's health. In other words, global greenhouse gas (GHGs) emissions, pollution, and environmental damage are all caused by excessive energy usage. For instance, Figure 1.1 illustrates the global the CO<sub>2</sub> emissions in different countries according to their region. This indicates that fossil fuels' combustion for transport sector, industry, heating, and power generation accounts for over 65% of worldwide greenhouse gas (Lelieveld *et al.* 2019).



**Figure 2.1** Worldwide CO<sub>2</sub> emission by continent/region (International Energy Agency 2019)

### 2.3 Climate Change and Sustainable Development

Climate and sustainability are the two imperatives of the 21<sup>st</sup> century while being interdependent and interrelated concepts. In the broad sense, climate change effects have been globally intensified over

the last few decades. For instance, the World Meteorological Organization (WMO) estimated that the average worldwide surface temperature in 2020 was  $1.2 \pm 0.1$  °C warmer than the historical average during the second half of the 19<sup>th</sup> century while the recent decade (2011–2020) was the warmest on record (World Meteorological 2022). Thus, it could be evidently inferred that the humans' wellbeing, ecosystems, and the stable climate that supports life on Earth all face acute threats from climate change (Li 2021). Moreover, the continuous rising intensity in atmospheric greenhouse gases emission has further exacerbated the climate change challenge with statistical prediction models on the subject matter indicating that the mean ambient temperature in the final two decades of this present century could increase by about 5 °C (Ukey and Rai 2021). Being the primary cause of the current global warming, issues surrounding climate change have sparked awakening cautions and actions among governments and organizations, thereby leading to such campaigns spearheaded by the intergovernmental panel on climate change (IPCC) alongside such events like the Paris Agreement and Kyoto Protocol (Sun *et al.* 2022). Similarly, climate-related migration has emerged as a unique discourse, and a plethora of policy, academic, development, and social areas are working to understand its complexity (Ferris 2020).

While the aftermath of climate change poses mounting hazards to people, planet and profit owing to its varying nature, sustainable development aims to alleviate its effect. The sustainable development notion, which dates back to the 1970s, emerged due to increased global awareness regarding the nexus between socioeconomic issues (including extreme poverty, inequality, and worries about prospective human wellbeing) and escalating environmental challenges (Darko, Zhang and Chan 2017). The essence of sustainable development concept, being presented at the Brundtland Commission, has delineated report which stressed that the environment is important to human security and fundamental life, alongside the current and future health of our economies (Darko and Chan 2017). Although the nitty-gritties of sustainable development are evident, nonetheless, there are many different hypothetical inputs that have led to frequently ambiguous perceptions by the research community. Del-Aguila-Arcatales *et al.* (2022) argued that this has evolved into an extended dialogue among academics who examined different interpretations of sustainable development while identifying various aspects of the notion which they summed up in three groups of economic, environmental, and social aspects.

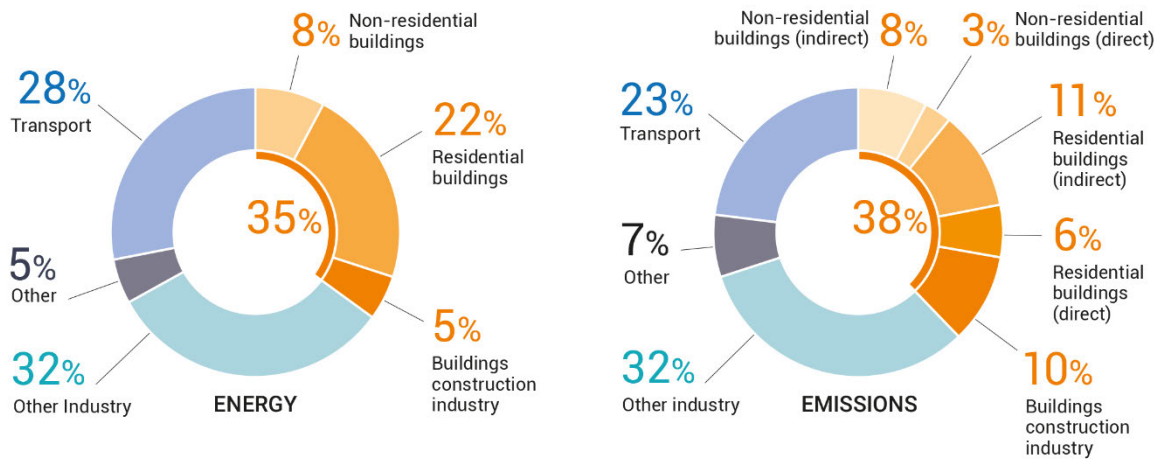
According to D'Adamo, Gastaldi and Morone (2022), the economic aspect includes all human-made assets that are largely focused on enhancing wellbeing for people, typically via spurring uptake of products and services. Moreover, this component focuses on fostering prosperity among people rather than merely maximizing profits for a select few excellent people and doing it within the parameters of what is environmentally permissible without violating fundamental human rights. Meanwhile, the

environmental aspect places enormous value and priority on preserving the resilience and adaptability of ecosystems so that the planet can continue to sustain humans with a decent standard of living (Baffo *et al.* 2023). As for the social component, it involves an individual's knowledge of the importance of achieving distributional justice, appropriate social service delivery, such as education and healthcare, gender equality and equity, alongside civic duty and involvement (Bogers *et al.* 2022). Thus, it could be said that these three facets of sustainable development are interdependent and mutual. As an illustration, it is vital to produce human capital to create wealth (economic aspect) that positively impact ecological integrity and resilience (environmental aspect) to attain high-quality social services, medical care, higher learning, and whatnot (social aspect). In sum, sustainable development is a form of integration among facets, and its realization necessitates these three components.

#### **2.4. The Built Environment Sector and Sustainable Construction**

In general, shelter is a fundamental human necessity that shields people from such inclement elements of nature as the sun, wind, rain, and snow. Besides, over 90% of all human life is spent inside of buildings while cities have become home to more than 50% of the world's population (Mohammad *et al.* 2022). On this wise, the built environment industry is committed to meeting this demand, along with other allied functional requirements, in an ecologically, economically, and socially sustainable manner. Thus, it is not an irony that this sector immensely contributes to both national and global economic growth via employment opportunities, infrastructural stock, increase in a country's gross domestic product (GDP), among others.

However, as opined earlier in the first chapter, this sector is criticized to be energy-intensive, resource-consuming, and carbon-emitting from concept to conclusion. Thus, it accounts for 40% and 30% of the world's final energy outlay and CO<sub>2</sub> emissions, respectively; leading to resource depletion, climate change and allied adverse effects on humans and ecosystem (Geng *et al.* 2019; Aghimien *et al.* 2021). The International Energy Agency (IEA) mentioned that the construction sector leads the poll in terms of global energy use and carbon footprint when compared to other sectors (see Figure 2.2). Specifically, the building energy use in Japan, the European Union, Australia, South Africa and the United States (to mention a few) accounted for 31%, 40%, 30% 40% and 40% respectively of each country's final end-use energy (Azis 2021; Kuwahara, Kim and Sato 2022; Agbajor *et al.* 2023; Ejidike *et al.* 2023). In the meantime, Wuni, Shen and Osei-Kyei (2019) highlighted that these worries have spurred practitioners and stakeholders within the industry and allied sectors to develop and apply strategies to assuage the sector's anthropogenic impacts, protect biodiversity, heighten efficiency and sustainability, and such like.

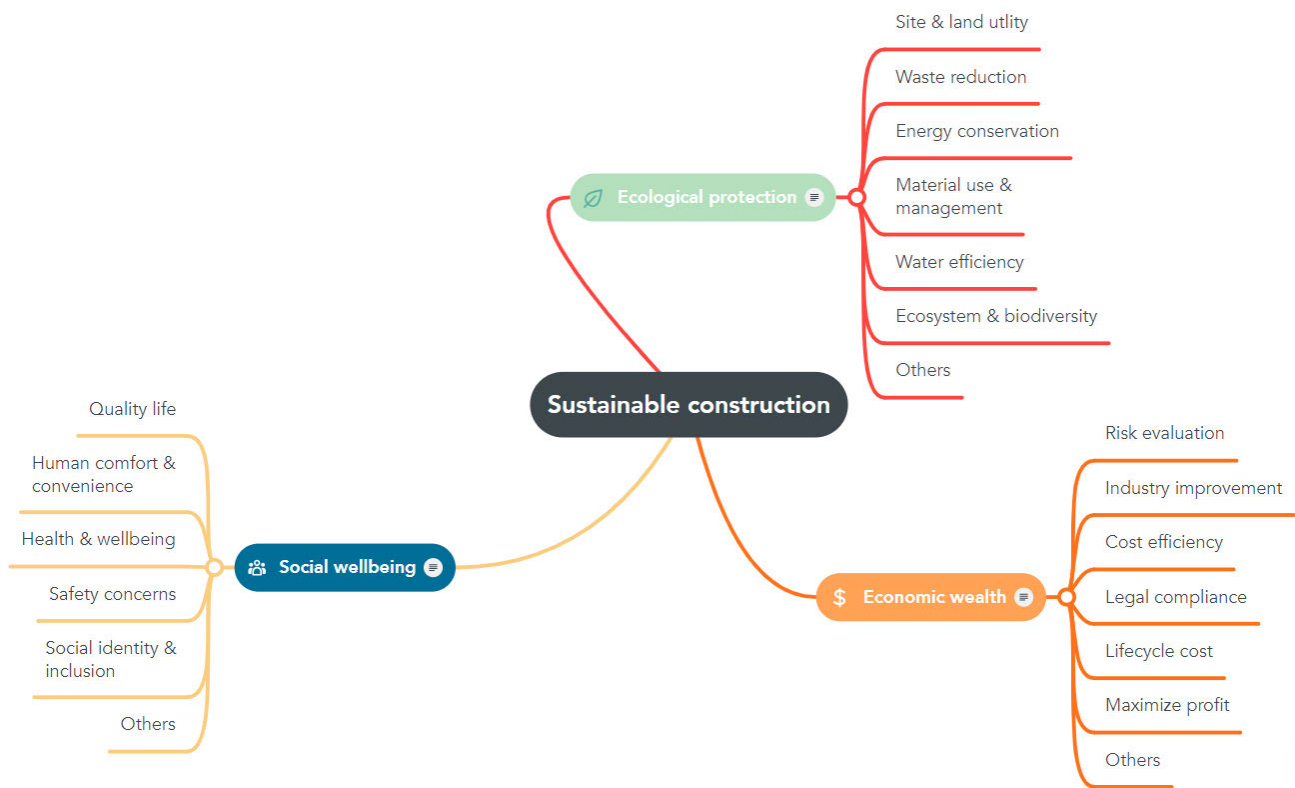


**Figure 2.2:** Global quota of final energy use and CO<sub>2</sub> emissions (IEA 2020a, 2020b)

Meanwhile, the built environment is a complex socio-ecological system that serves as both a source of challenges and a centre for problem-solving (Zwierzchowska *et al.* 2022). This sparked the concept of sustainable construction which is an important principle for mitigating building sector's adverse effects while promoting sustainable development as a result (Lima *et al.* 2021). In simple terms, sustainable construction is a subset of sustainable development established on threefold principles of resource management, lifecycle design, as well as design for humans and environment (Ershadi and Goodarzi 2021). To put it plainly, the emphasis of resource management is on reducing, reusing, and recycling natural and limited resources used in the production of built products. According to Liu *et al.* (2021), the lifecycle design aims to hit a balance between ecological concerns and the conventional considerations that often influence choices and options in the planning, construction, and maintenance phases of a built product. Meanwhile, the balance between environmental quality within and outside the constructed product along with human's wellbeing and happiness is expressed in the design for human and environment.

It is noteworthy that sustainable construction depicts an identical feature of sustainable development from an ecological, economic, and social perspective (see Figure 2.3). The ecological aspect aims to avert damaging impacts on the ecosystem via the wise and creative use of natural resources, waste reduction, and the preservation and improvement of the environment (Goh *et al.* 2020). By properly choosing and utilising resources such as energy, water, materials, and manpower more efficiently, Solaimani and Sedighi (2020) mentioned that the economic aspect places an emphasis on profit maximization while lowering capital and operation expenses. The social aspect focuses on improving the human's existence and quality life by meeting such fundamental necessities like housing alongside assuring convenience, identity, and choice (Mushi, Nguluma and Kihila 2022b). Overall, the

overarching goal of sustainable construction is seen in the need to reestablish and preserve between the natural and built environment while building communities that uphold human dignity and promote economic fairness.



**Figure 2.3:** A typical illustration of sustainable construction facets (Developed by author)

## 2.5 Green Building: An Overview

To start with, the genesis of green building may be linked back to the energy crisis brought on by the Organization of the Petroleum Exporting Countries (OPEC) oil embargo at the turn of the twentieth century (Wuni, Shen and Osei-Kyei 2019). This fuelled some doubts and queries among global leaders and industry experts on the usual view of relying on fossil fuel for energy. Consequently, stakeholders within the built environment kickstarted solution pathways that can alleviate buildings and allied infrastructures' dependence on fossil fuels as an energy source. As opined by (Agbajor and Mewomo 2024), diverse research endeavours were carried out, novel renewable energy solutions (like solar photovoltaics) were introduced, while iconic structures to illustrate high-performance buildings were constructed during this era. Therefrom, green building has witnessed explosive growth in terms of research and development globally in the past decades.

Meanwhile, it is worth mentioning that the terms "green building" and "sustainable construction" are frequently and synonymously used. Notably no set standard abounds for which one to employ, but it

is noteworthy that a green building is a finished edifice that is planned, constructed, and maintained according to the sustainable construction principles (Darko and Chan 2016). In other words, the concept of sustainable construction in the building sector can be seen in the finished products known as green buildings. Nonetheless, some scholars argued that these two terms employ the same set standards which led to providing a contrast among them. According to (Li *et al.* 2023a), the major distinction between green building and sustainable construction is that the former is skewed towards ecological facet while the latter embraces the ecological, economic, and social components.

Undeniably, for pragmatic adoption of green building, regulations and policies are very essential. Since the emergence of green building concept, diverse policies have been introduced by governments, decisionmakers and key construction industry practitioners to hasten its deployment and adoption. While green building adoption is compassed about with good facets such as drivers and benefits, several obstacles often bewilder its application. Meanwhile, promotion strategies and incentive schemes are influential for green building adoption, while rating systems and standards are vital to abate ecological hazards and realizing climate-resilient built environment alongside low-carbon societies. To this end, this section presents an overview on the following:

- Global green building regulations and policies.
- Green building adoption and implementation.
- Incentive mechanisms for green building development.
- Green building rating systems.
- Digital technologies in green building development.

### **2.5.1 Global green building regulations and policies**

This part specifically and succinctly provides prominent policies being endorsed and implemented in various world regions with the overarching objective of advancing green building.

#### **2.5.1.1 Asia**

Green building (hereafter, GB) codes and policies became imperative in Asia as the region chiefly contributes to global CO<sub>2</sub> emission. Considering this, several nations within this region have made concerted efforts to enact requisite GB policies and standards. For instance, the Japanese government launched the Energy Conservation Law in 1979 to brace up the fundamentals of energy conservation and management (Zhang *et al.* 2019b). The evaluation criteria for the policy comprise rational and optimum resource utilization, urban heat island mitigation and natural environment conservation. Also, the country introduced the energy efficiency building codes (being a voluntary standard) for

residential and commercial buildings as part of its ambitious goal of realizing net-zero energy buildings in 2050 (Oshiro, Masui and Kainuma 2018). Singapore has been leading-edge in pragmatic adoption of GB policy in Southeast Asia and beyond. Being an island city state with 100% urban population and energy-consuming building sector, Singapore's building and construction authority (BCA) enacted a national policy called "Green Mark" in 2005 in an attempt to encourage the building sector to create more eco-friendly structures (Siva, Hoppe and Jain 2017). Ideally, three successive series of masterplans were initiated in this scheme to amplify the nation's GB campaign while focusing on the keen target of having at least 80% of Singapore's buildings to be green by 2030 (Hwang, Zhu and Ming Jonathan Tan 2017).

In China, the central government introduced the Green Building Action Plan (GBAP) to curb continual anthropogenic activities from China's construction sector due to the country's socio-economic boom and rapid urban sprawl (Zhang *et al.* 2019b). A recent review report indicated China's GB policy advancements such as the top-down GB governance system, the updated GBAP to Green Building Creation Action Plan in 2020 alongside its amplified GB scope and ardent goals to include NZEBs, passive ultra-low energy buildings, green eco-friendly urban zones and so on, as the country strives towards the carbon neutrality target by 2060 (Alabi *et al.* 2023; Hu *et al.* 2023). Moreover, China's GB policies are veered towards five core pedestals, including reducing economic disparity and fostering regional cooperation, enhancing judicial and regulatory frameworks, utilizing regional uniqueness to adopt innovative policy, creating an information dissemination platform, and establishing a market-driven green finance system.

Promisingly, developing Asian countries such as Vietnam, Indonesia, Philippines, Malaysia are gainfully involved in establishing their location-based GB guidelines and policies. The Vietnam government initiated strategic actions to facilitate GB upgrade by applying a decision-making model all over the nation in 2009 while Hanoi and Ho Chi Minh City became the first test bed cities to be certified as GBs (Nguyen *et al.* 2017). Consequently, the government introduced the National Green Growth Strategy that saddled real practitioners with the obligation of adopting green measures while constructing or retrofitting modern and existing buildings respectively (Zhang *et al.* 2019b). In Indonesia, the Minister of Public Works' rule no. 2 of 2015 covering GBs serves as the fundamental guide for establishing eco-friendly structures following the enactment of the DKI Jakarta Governor's GB Regulation in 2012 (Sahid, Sumiyati and Purisari 2021) with GB performance metrics centred on CO<sub>2</sub> emission reduction and energy saving. In Philippines, the Energy Efficiency and Conservation Act was issued towards efficient and prudent energy use across all sectors via the formulation, development, and execution of energy efficiency and conservation plans and programs (Franco, Pawar

and Wu 2021). Its policy obliges enhancing GB initiatives across Indonesian municipalities via the local government units towards an ambitious 70% rate decarbonization target by 2030. Meanwhile, the establishment of a Malaysian-based GB policy became evident at the launch of the Green Building Index during the Green Design forum in 2009 which aimed at evaluating Malaysian buildings' environmental design and performance (Samari *et al.* 2013).

### **2.5.1.2. Europe**

In Northwestern Europe, Finland, Sweden, and the United Kingdom (UK) are ahead of the curve regarding GB policies. Finland, for instance, has set a goal of achieving carbon neutrality in the built environment by 2035 (Hirvonen *et al.* 2022). To this end, her government ensured the use of wood in building construction to facilitate the utilization of renewable and carbon-neutral GB materials, while enacting the eminent Finnish Building Information Foundation's (RT) certification system as one of its strategic programs to create and maintain eco-friendly edifices (Hirvonen *et al.* 2022). Similarly, the Passive House Standard was established in Sweden in the nation's pragmatic effort to promote ultra-low energy buildings and improve the environmental performance of structures (Niskanen and Rohracher 2022). For the UK, the Code for Sustainable Homes as well as the Green Deal constitute the set of GB policies to amplify sustainable construction practice in the region (Pretlove and Kade 2016). Moreover, the government specifically launched targets for zero-carbon homes that required new buildings to meet minimum energy efficiency standards. The GB policies were also endorsed by the Dutch government which include the Energy Performance of Buildings Directive in 2010, that sets minimum energy performance standards for new and existing buildings (van der Bent *et al.* 2021), and the Green Lease concept in 2016, which encourages landlords and tenants to collaborate on energy efficiency improvements (Rotmann 2017).

In Central Europe, the German government enacted several GB policies in place, including the Energy Saving Ordinance (EnEV) that sets minimal energy efficiency standards for new and existing buildings; the Renewable Energy Heat Act (EEWärmeG), which requires the use of renewable energy sources (RES) for heating and cooling (Bauermann 2016). Likewise, the Building Energy Act (GEG) was issued to consolidate and update diverse energy regulations for German houses while the Energy Efficiency Strategy for Buildings (ESG) was initiated to outline a holistic approach for energy efficiency enhancement and CO<sub>2</sub> emissions reduction from buildings (Singhal *et al.* 2022). Similarly, the Swiss government endorsed some vital GB standards to ensure climate-resilient infrastructures. In 1978, the Swiss Society of Engineers and Architects (SIA) developed the SIA Energy Efficiency Path which offers a synergistic structure for designing and constructing buildings that meet high energy efficiency standards (Zuberi *et al.* 2020). Also, the Swiss Sustainable Building Standard

(SNBS) was enacted as a performance-based standard that measures the sustainability of buildings through a series of criteria that address environmental impact, social responsibility, energy efficiency and economic viability (Beyeler, Beglinger and Roder 2009). Other Swiss-based GB policies include the Swiss Energy Strategy 2050 – to increase RES in the country's energy mix via energy labelling (Zuberi *et al.* 2020), the CO<sub>2</sub> Act (to lessen Switzerland's CO<sub>2</sub> emissions by 50% in 2030), and the 2000-Watt Society (aims to achieve per capita energy consumption to 2000 Watts by 2050) (Thaler and Kellenberger 2017).

### ***2.5.1.3 North America***

The United States of America (USA) and Canada are the vanguards towards GB advancement in this region. Due to the topmost importance accorded to achieve a carbon-free society, the US government issued several initiatives and guidelines. In 2013, the US Department of Energy initiated the Zero Energy Ready Homes program to grant certifications for homes that are designed to be extremely energy-efficient and have the potential to produce as much energy as they consume (Wang *et al.* 2021). Meanwhile, a more rigorous GB standard named Living Building Challenge, endorsed earlier in 2006, plays emphasis on producing buildings that are self-sufficient and regenerative, thus requiring US buildings to meet strict criteria related to energy, water, materials, and indoor environmental quality (Hu, Cunningham and Gilloran 2017). In specifics, state-oriented edicts were enforced in some US regions. For example, the New York City Green Buildings Laws were publicly passed aiming at promoting regional-based GB, including Local Law 84, demanding building owners to report their energy use, and Local Law 87, which requires large buildings to undergo an energy audit and retro-commissioning every ten years (Dougherty and Jain 2023). Similarly, California Green Building Standards Code (CALGreen), being an obligatory GB code issued in California in 2011, necessitates new buildings to meet certain sustainability requirements, such as reducing water consumption and using energy-efficient lighting (Skillington *et al.* 2022). However, in Canada, the government launched the Federal Buildings Initiative in 1991 which seeks to reduce carbon emissions from federal buildings by 80% below 2005 levels by 2050 (Liming, Haque and Barg 2008). The initiative comprises enhancing energy efficiency via RES and reducing water consumption in federal buildings. Also, the National Energy Code for Buildings (NECB) that sets minimum standards for energy efficiency in new and renovated Canadian buildings was promulgated in 1997 and revamped at five years intervals to keep pace with advances in building technology and to encourage the adoption of more efficient building practices (Schreiber, Jandaghian and Baskaran 2021).

### ***2.5.1.4 South America***

Brazil has been at the forefront of augmenting GB standards in South American terrain via its labelling

programs comprising the Regulation for Energy Efficiency Labelling of Commercial, Service and Public Buildings (RTQ-C) and the Regulation for Energy Efficiency Labelling of Residential Buildings (RTQR) released in 2009 and 2010 respectively (Soares Geraldi *et al.* 2022). For Brazilian buildings to be RTQ-C and RTQR labelled, they must comply with the standard criteria which considers building envelope performance, efficiency and capacity for lighting system, HVAC system and allied household equipment (Batista, Rovere and Aguiar 2011). Furthermore, the established National Solid Waste Policy was designated to offer guidelines that ensures solid waste management, including construction and demolition waste, while the National Policy on Climate Change established in early 2000 (Peres, Campos-Silva and Ritter 2023), veered towards greenhouse gas (GHG) emissions reduction and promote sustainable development across the building industry and allied sectors. Meanwhile, Argentina has a similar comparison with Brazil regarding the GB policy subject with her government introducing the acclaimed National Green Building Program (Zepeda-Gil and Natarajan 2020) which stresses on promoting the adoption of sustainable construction practices and provides guidelines for sustainable building design, materials, and operation. Besides, the Energy Efficiency Law and the National Solid Waste Law, with similar objectives as that of Brazil were implemented by the Argentine government (Recalde and Ramos-Martin 2012).

#### **2.5.1.5. Oceania**

This region comprises certain set of regulations to counteract climate change and foster ecofriendly construction practices throughout the building lifecycle. In Australia, some GB policies were enacted to lessen the construction industry's negative environmental impacts and encourage ecologically conscious building techniques. For an illustration, the National Construction Code was established in 1996 as a performance-based policy to advance the building sector innovation in terms of energy conservation and sustainability effectiveness (Armstrong *et al.* 2017). Specifically, this code founded minimum criteria for energy efficiency, safety, health and sustainable design in newly built structures and substantial refurbishments in Australian terrain. Some years after, the Climate Initiative was introduced as a widespread reaction to the rising levels of atmospheric CO<sub>2</sub> emission within Australian landscape (Moroni 2012) while the government acknowledged and promoted construction industries that comply with this such. Also, the Building Sustainability Index and Victorian Energy Upgrades program were developed in New South Wales and Victoria respectively as territory-based initiatives. Other policies such as the Renewable Energy Act and the National Australian Built Environment Rating System (NABERS) (Residovic 2017) were enacted to encourage the utilization of renewable resources for ideal environmental performance of buildings within the country.

Similarly, initiatives such as the Homestar, the Building Code and NABERSNZ constitute the range

of GB policies to enable sustainable built environment in New Zealand. Established by country's Green Building Council, the Homestar aimed to serve as a nationwide residential building rating tool to assess the environmental performance and conservation of energy of dwellings (Ade and Rehm 2019). Likewise, the NABERSNZ was developed to measure the impact of occupant behaviour on resource efficiency and the sustainability of commercial buildings that have been modified (Aigwi *et al.* 2020), while the Building Code was enacted to specify the basic criteria for planning, development, and optimal operation of New Zealand buildings (Mayer and Boston 2022). Also, Zhang *et al.* (2023a) highlighted the government's impact by instituting the Energy Efficiency and Conservation Authority which give guidelines, tools, and rewards to boost energy-efficient construction techniques, such as the Warm Up New Zealand program.

#### **2.5.1.6. Africa**

Although this continent trails behind other climes on the subject matter, a few countries are making cheering efforts and substantial progress with South Africa being a leading edge in green building development in the region via its mix of policies. Categorically, strategic standards like the National Building Regulations and Building Standards Act (NBRBSA), the Energy Efficiency Strategy of South Africa (EESSA) and the Low Carbon Economy Strategy (LCES) established in 1997, 1998 and 2013 respectively, constitute a hub of national-based policies (Twum-Darko and Mazibuko 2015; Huxham, Anwar and Nelson 2019). Overall, these policies strive to abate the carbon-footprint across all sectors due to over-reliance on its coal-denominated energy infrastructure. In essence, LCES puts core focus on green building optimization, while NBRBSA mandates new structures to adhere to its energy efficiency and sustainability requirements for building services systems. From the provincial lookout, several municipalities in South Africa have implemented their own green building policies and initiatives. For example, the City of Cape Town has a green building policy that emboldens optimal resources utilization and conservation alongside sustainable building practices at the design and construction phases (Agbajor and Mewomo 2024).

In Ghana, the Renewable Energy Act was passed in 2011 to upscale the development and use of RES in different building types while issuing incentives such as tax exemptions and rebates to advance the law (Aboagye *et al.* 2021). Other relevant Ghanaian GB policies include the National Climate Change Policy, Energy Efficiency Standards and Labelling Program, and Sustainable Energy for All Action Agenda which were established in 2013, 2014 and 2015 respectively (Agyekum 2020; Nyasapoh, Elorm and Derkyi 2022). In North Africa, Egypt developed the Building Energy Code in 2013 which applies to both residential and commercial buildings, governing such areas as building envelopes, lighting, and HVAC systems (Twum-Darko and Mazibuko 2015). Also, the Feed-in Tariff (FiT)

program was introduced in 2014 to encourage the development of renewable energy projects in Egypt by offering a fixed electricity price generated from RES, like solar and wind power, and has led to an increase in the installation of renewable energy systems in buildings (Abdelhady, Borello and Santori 2015). For Nigeria, the Building Energy Efficiency Guideline developed by the Energy Commission of Nigeria (ECN) (Geissler, Österreicher and Macharm 2018), provides list of guidelines and recommendations for the selection of building materials, lighting, HVAC systems, and renewable energy sources.

### **2.5.2 Adoption and implementation of green building**

At the outset, green building, being a renowned revolutionary theory and practice in the construction industry, is suggested as a solution to numerous global ecological challenges. Nonetheless, some paradigms influence the way it is being embraced. In specifics, several themes, including benefits, drivers, barriers, critical success factors, promotional strategies, and such like, were regarded by stakeholders, researchers and practitioners as the vanguard towards the acceptance and application of green building development (Darko *et al.* 2017). Mushi, Nguluma and Kihila (2022b) mentioned that these listed issues span across social, economic, and environmental sustainability indicators. An evaluation from regional outlook showed that they are crucial to both developed and emerging countries. For instance, Lai *et al.* (2023) pointed out that green building has advanced quickly in Southeast Asia owing to the conflict between the land scarcity and the growing population. Indeed, sustainable buildings are highly valued today due to the merits green building practices offer. As stated by Ojo-Fafore, Aigbavboa and Remaru (2018), some benefits of adopting green building include improved occupant's comfort and wellbeing, natural resources conservation, ecological protection, reduced greenhouse gas emission, increased occupants safety and whatnot. Also, economic benefits like increased energy savings, lower water usage, reduced operating costs and higher market value were highlighted by Dwaikat and Ali (2018). As an illustration, Dwaikat and Ali (2018) compared the financial performance of an operational green building to the industry benchmark to assess its present and future potential. Their results achieved over 70% energy savings and inferred that real estate investors should consider the financial advantages of green buildings' lower energy use.

Consequently, these benefits of green building created some drivers to its application. An in-depth study by Darko, Zhang and Chan (2017) unveiled several propelling factors to green construction and affirmed that these could be driven individually, corporately, externally, project-based or property-based. Devine and McCollum (2019) argued that foreign direct investment in emerging market nations

is a significant driving force to promote green construction. Likewise, Darko *et al.* (2018) asserted that the uptake of green building technology is greatly influenced favourably by business-related factors like improved working environment, higher building value and increased productivity of building occupants. It could be surmised that these drivers and many more, may either inspire or put emphasis on participants to develop green buildings.

Regardless of the aforesaid benefits and drivers, Wuni, Shen and Osei-Kyei (2019) declared that the acceptance rates seems slow and ineffective in diverse world regions, especially in developing economies. Notably, several factors act as impediments to green building adoption. For instance, long payback periods (Ahn *et al.* 2013), paucity of funds (Rock *et al.* 2019), insufficient economic incentives (Shen, Zhang and Long 2017), perceived high costs (Mustaffa, Mat Isa and Che Ibrahim 2021) were identified as substantial cost-based barriers to green building adoption in the USA, Australia, China and Malaysia respectively. Moreover, Chan *et al.* (2018) argued that increased green building costs, scarce government incentives and lack of finance mechanisms like bank loans constitute topmost barriers in developing countries like Ghana. However, some panaceas to such barriers and strategies to promote green building adoption were suggested by several researchers. These include public awareness of green building benefits (Mewomo, Agbajor and Mogaji 2023), availability of competent and proactive stakeholders (Darko and Chan 2018), interdisciplinary network of construction professionals (Hwang, Zhu and Tan 2017), executive management support (Li *et al.* 2014), adequate financial incentives and innovative fiscal arrangements (Chan *et al.* 2018).

### **2.5.3 Incentive mechanisms for green building development**

To stimulate the growing focus on sustainable development in the construction sector, availability of incentive schemes is vital to overcome the economic-related barriers to green building practices (Fan and Wu 2020). According to Olubunmi, Xia and Skitmore (2016), these incentives can either be external or internal. The latter enables recipients to be motivated out of choice due to the attraction of green buildings benefits. In contrast, the external incentive forces receivers to comply with predetermined conditions or standards before receiving benefits. However, Fan and Wu (2020) argued that policymakers must first understand the fundamentals of incentive schemes in order to make any necessary adjustments. At such, both external and internal incentives may be monetary based or not (Olubunmi, Xia and Skitmore 2016). In finance-based cases, Fan and Wu (2020) pointed out the essence of conducting the cost-benefit analysis when promoting highly sustainable structures. Meanwhile, some scholars opined that while both forms of incentives are essential, it is needful to consider their effects. Saka, Olanipekun and Omotayo (2021) argued that most green building

practitioners may opt for internal incentives in form of remunerations or reimbursements since they can decide whether to accept them or not. Onuoha, Aliagha and Rahman (2018) modelled the impacts of green building incentives against supply factor in green property market and concluded that the most important impact on the supply and investment of green commercial real estate was determined to be financial green tax incentives.

From monetary outlook, Akomea-Frimpong *et al.* (2022) affirmed recently that global events have focused attention on inclusive project financing mechanisms that address global warming and reduce greenhouse gas emissions in the construction and operation of buildings. According to Debrah, Chan and Darko (2022b) and He *et al.* (2022a), prominent financing schemes utilized nowadays can be in form of green credit, green fiscal investment, green tax, carbon finance, and green insurance. It is noteworthy that several studies have identified the government as the core playmaker in deploying these monetary schemes. For example, the Federation of Canadian Municipalities, which administers the Green Municipal Fund, offers grants to concerned communities for initiatives aimed at lowering carbon emissions and enhancing the resilience of municipal infrastructure (Rana *et al.* 2021). Similarly, Germany provides monetary incentives for ecologically-sound construction via initiatives like the Energy Efficient Building program of the KfW Development Bank (Reis 2022). Besides the government, some corporate bodies and private organizations are making giant strides in this regard. Debrah, Chan and Darko (2022b) reported that Acorn Holdings in Kenya and International Housing Solutions in South Africa have made noble progresses in the issuance of green bonds for financing environmentally friendly affordable dwellings.

In brief, financing mechanisms offer profound impetus to green construction. Nonetheless, the impact of these schemes regarding subsidies cannot be underrated when incentivising green projects. Nowadays, consumer behaviour is playing a crucial role in green construction market than previously thought. An empirical study by He and Chen (2021) proved the fact by inferring that the incentive effect of subsidies on consumers was greater than that of subsidies on developers. More so, it is needful to carefully consider the barriers, criticisms, obstacles, and promotional strategies that encompass green building incentives.

#### **2.5.4 Green building rating systems (GBRS)**

With sustainable building concepts are becoming more alluring in this current era, incessant efforts are being taken to intensify its worldwide adoption. A giant step taken is the institution of the global network for green buildings, known as *World Green Building Council* (World GBC) in 1999, having over 100-member countries (Zhang, Wu and Liu 2018). From there, each member country has

established its GBC along with several GBRS to optimize resource-efficient, carbon-neutral and climate-resilient building typologies (Janda *et al.* 2021). For example, the UK GBC launched the Building Research Establishment Environmental Assessment Method (BREEAM) in 1990 (Tleuken *et al.* 2021) and also introduced the Code for Sustainable Homes in 2006 to rate and certify the sustainability performance of newly constructed homes in the region (Bon-Gang 2018). Meanwhile, Li *et al.* (2019a) reported that the European Union established the Energy Performance Building Directive (EPBD) which seeks to achieve the net zero energy buildings (NZEBS) in 2050 via setting out the minimum energy performance requirements for new and existing buildings, by developing the Energy Performance Certificate (EPC). The EPC assists in predicting the buildings' annual energy demand and spurs market demand for energy-efficient buildings.

In Asia, China's Ministry of Construction unveiled the Assessment Standard for Green Building (ASGB) in 2006 as the nation's local GBRS to provide sustainability ratings for structures there (Bon-Gang 2018). South Korea established the Building Energy Efficiency Certification System (BEECS) in 2001 to foster the spread of high energy-efficient buildings by assessing and endorsing building energy performance (Park *et al.* 2015). Likewise, Malaysia adapted Singapore's Green Mark certification system (established in 2005) (Azis 2021) to develop its Green Building Index (GBI), which acts as its first wide-ranging grading system for assessing the ecological layout and functioning of buildings (Aghili *et al.* 2019). Meanwhile, in order to grade and certify green infrastructure across the Middle East and North Africa region, Qatar introduced the Global Sustainability Assessment System (GSAS) in 2009 (Rybkowski *et al.* 2017). In sub-Saharan Africa, South African government issued the EPC standard for buildings to propel the switch towards a green construction sector and promote sustainable development (Agbajor and Mewomo 2024). Other certification systems such as LEED, Green Star, Green Globes, CASBEE are deployed in the United States, Australia, Canada and Japan respectively (Shan and Hwang 2018a).

Figure 2.4 illustrates a global atlas for green building rating tools utilized by various countries. In sum, Bon-Gang (2018) stated that these holistic frameworks are established to evaluate and verify the sustainability and greenness of buildings. Generally, the widely utilized assessment parameters comprise energy, water, material resource, site, interior space, land, and external environment as well as innovation. Some scholars compared these rating tools across continents (Varma and Palaniappan 2019) as well as between developed countries and emerging economies (Zarghami and Fatourehchi 2020) to understand their dynamics and feasibility. However, whether these GBRS parameters truly influence criteria like energy efficiency and indoor thermal comfort fuelled debates among researchers and practitioners. It is essential that these rating systems surpass design-based standards only (He *et*

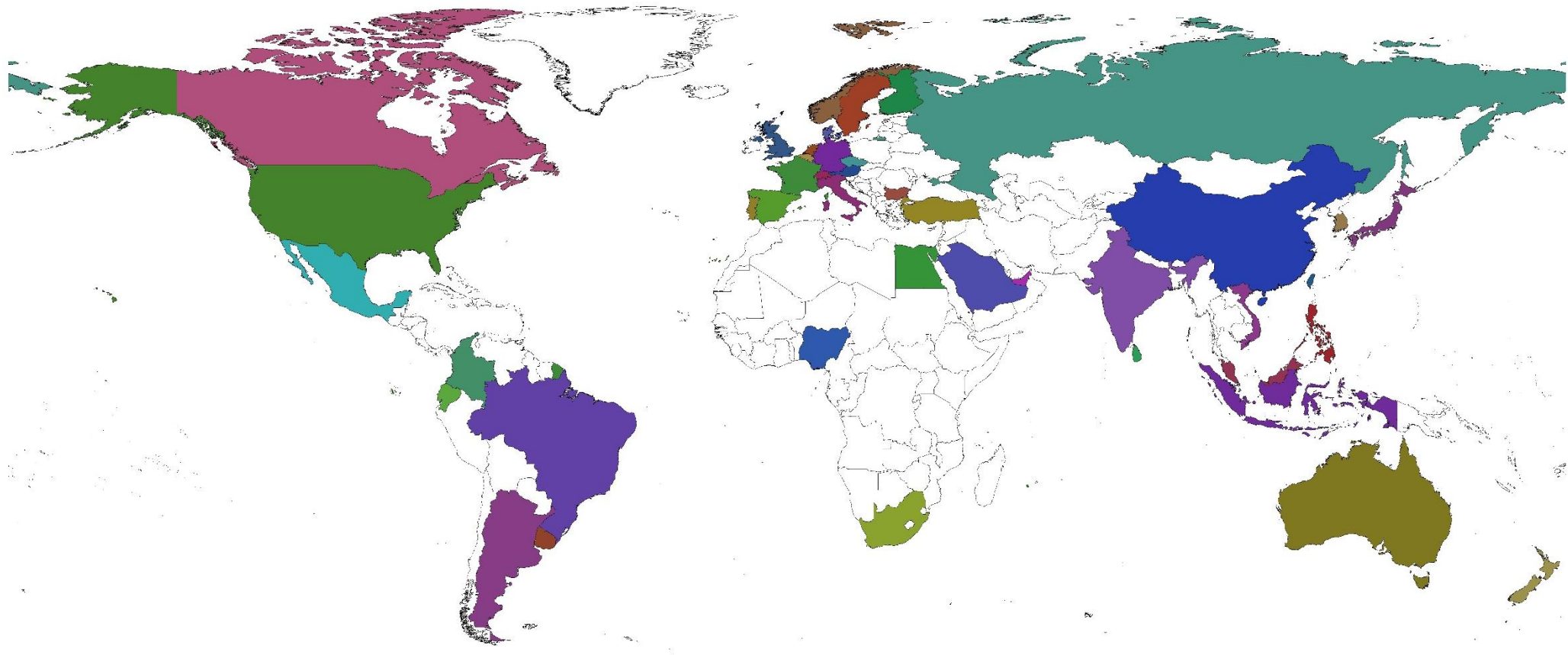
*al.* 2022b) while the essence of creating a link between different aspects of GBRS and actual building performance cannot be overlooked.

### **2.5.5. Digital technologies in green building development**

As the digital revolution continues to address complicated difficulties, it also has a beneficial effect on the building industry. Thus, utilizing cutting-edge digital technologies to green building is a great way to raise the effectiveness, adaptability, and sustainability of the construction sector. Preferably, all sustainability facets have been addressed via these technologies and it is explicitly presented in Table 2.1 that they are essential for reasonable management of resources throughout the lifespan of building construction. Apparently, the integration of building information modelling (BIM) is illustrated to be the dominant digital technology applied in all case scenarios considered.

Regarding each phase of construction, Agbajor and Mewomo (2022a) mentioned that incorporating these digital technologies, particularly at the project planning stage can be an excellent way to address potential construction-related issues and positively affect the remainder of the construction lifecycle. For instance, the BIM technique is being utilized in choosing sustainable materials and generating innovative building components (Jayasinghe and Waldmann 2020), while artificial neural network was employed to determine the working strength of novel green building materials such as hydrated-lime-activated rice husk ash (Onyelowe *et al.* 2021). Likewise, the application of blockchain can be beneficial in the early planning of ledger transactions relating to the development of green building projects. However, the major query in this respect is that these technologies are skewed towards green building design and construction stage only. It is therefore essential to explore other aspects of entire lifecycle.

Meanwhile, the uniqueness of these digital technologies is expressed in green building sustainability aspects. Of note is BIM's importance in each facet of economic, ecological, and social sustainability. According to Filho *et al.* (2022), BIM models can be deployed to assess the long-term viability of low-income green buildings and their supporting materials. In another vein, Pomponi *et al.* (2021) used machine learning models to evaluate the entire lifecycle of embodied energy in buildings and provide more decision support while establishing higher confidence levels than usual optimization strategies.



- <all other values>
- Argentina - LEED
- Australia - Green Star, NABERS
- Austria - OGNI, Total Quality
- Belgium - LEnSE
- Brazil - AQUA, LEED Brasil, BREEAM Brasil
- Bulgaria - DGNB
- Canada - GreenGlobes
- China - CGBL, Three Star
- Colombia - SACE
- Czech Republic - SBToolCZ
- Denmark - BEAT 2002, DGNB
- Ecuador - LEED
- Brazil - AQUA, LEED Brasil, BREEAM Brasil
- Egypt - Green Pyramid
- Finland - PromicE, BeCost
- France - HQE, Escalre, BREEAM France
- Germany - DGNB, GABI, BREEAM DE
- Hong Kong - HK-BEAM
- India - GRIHA
- Indonesia - GreenShip
- Italy - Protocollo ITACA
- Japan - CASBEE
- Luxembourg - BREEAM LU
- Malaysia - Green Building Index
- Mexico - SICES, LEED Mexico
- Netherlands - BREEAM-NL, SIMAPRO
- New Zealand - Green Star NZ
- Nigeria - Green Star-SANG
- Norway - BREEAM NOR
- Philippines - BERDE
- Portugal - LiderA, SBTool Portugal
- Russia - BREEAM Russia
- Saudi Arabia - Mostadam
- Singapore - Green Mark
- South Africa - Green Star SA, SBAT
- South Korea - G-SEED
- Spain - VERDE, GBC Espana
- Sri Lanka - GREENSL
- Sweden - Miljöbyggnad, Swan EcoLabel, BREEAM SE
- Switzerland - Minergie
- São Tomé and Principe -
- Taiwan - EEWH ABRI
- Turkey - BEST Certification System
- United Arab Emirates - Pearl Rating System
- United Kingdom - BREEAM
- United States of America - LEED, BEES 4.0, GreenGlobes
- Uruguay - Green Globes, LEED
- Vietnam - LOTUS

**Figure 2.4:** Global atlas of green building rating systems (Source: Developed by author)

**Table 2.1:** Digital technologies (DT) applied for green building development

DT	Phases of green building lifecycle					Resource management				Sustainability			References
	GBD	GC	GBM	POE	LCA	IEQ	EE	WE	MR/WM	E <sub>n</sub> S	E <sub>c</sub> S	SS	
AI		✓					✓		✓			✓	(Hendiani and Bagherpour 2019; Tushar <i>et al.</i> 2019; Duan <i>et al.</i> 2021b)
ML	✓		✓	✓					✓				(Onyelowe <i>et al.</i> 2021; Stjelja, Jokisalo and Kosonen 2022)
IoT							✓			✓			(Tushar <i>et al.</i> 2018; Goudarzi <i>et al.</i> 2021)
BIM	✓		✓		✓		✓	✓		✓	✓	✓	(Inyim, Rivera and Zhu 2015; Liu <i>et al.</i> 2019a; Liu <i>et al.</i> 2019c; Najjar <i>et al.</i> 2019; Tushar <i>et al.</i> 2019)
RBT		✓	✓				✓			✓			(Panda, Paul and Tan 2017; Lafhaj and Dakhli 2019; Rodriguez-Gracia <i>et al.</i> 2019; Alhumayani <i>et al.</i> 2020)
BCH	✓									✓			(Liu <i>et al.</i> 2019b; Wu <i>et al.</i> 2022)
AR/VR							✓						(Shan 2021)

**Notes:** **GBD:** Green Building Design; **GC:** Green Construction; **GBM:** Green Building Materials; **POE:** Post-occupancy Evaluation; **LCA:** Lifecycle Assessment; **MR/WM:** Materials Recycling/Waste Management; **E<sub>n</sub>S:** Environmental Sustainability; **E<sub>c</sub>S:** Economic Sustainability; **SS:** Social Sustainability; **AI:** Artificial Intelligence; **ML:** Machine Learning; **IoT:** Internet of Things; **BIM:** Building Information Modelling; **RBT:** Robotics; **BCH:** Blockchain; **AR/VR:** Augmented Reality/Virtual Reality

**Source:** (Agbajor and Mewomo 2022a)

Besides the spectrum of sustainability, the efficient use of all available building-related resources with these revolutionary digital technologies is imperative for sustainable buildings of this era. Some studies alluded that integrating these modern technologies can improve energy conversion and conservation in existing buildings in a realistic way. Artificial intelligence, for example, was coupled with Petri net model to create an environment that can produce biogas energy for buildings (Shahsavari *et al.* 2021) while machine learning models can assist in material recycling and waste management (Duan *et al.* 2021a). Also, the internet of things (IoT) technology can operate optimally in energy management to enhance interconnectivity among building users while the green internet of things (G-IoT) was suggested as a unique technology to reduce the environmental impacts of buildings while facilitating ecofriendly houses and smart cities (Yang *et al.* 2021). According to (Liu *et al.* 2019b), BIM can be fruitfully applied as a decision-making tool that provide water-saving capacities in the design and construction of modern buildings.

To sum up, in this era where intricate high-performance buildings are advocated, these technologies can act as huge game changers. Thus, green buildings may have improved occupant comfort and wellness, reduced resource consumption, and increased energy efficiency by utilizing them in a bid to create a more ecologically sound built environment.

## **2.6 Strategic Energy-Efficient Measures for Green Buildings**

The essence of strategic optimal energy-saving approaches for green building cannot be overstated. Without hesitation, this section provides some brief reasons for enhancing energy-efficiency in buildings, while the energy-efficient strategies ranging from nature-based solutions and renewable energy measures to passive building envelopes were discussed in the subsections that follow.

### **2.6.1 Why improve energy efficiency in buildings?**

By and large, energy-efficient buildings are crucial strategy for reducing global warming and promoting sustainable development. They can be planned, built, and operated in a way that makes the best use of available resources and limits the release of dangerous pollutants. In sum, some basic rationale for optimizing energy efficiency in buildings are briefly highlighted below.

#### ***2.6.1.1 Reduces energy demand and improve long-term cost savings***

Since buildings act as large energy-consuming edifices, it is essential to combat energy-intensive advancements in new and existing buildings. Thus, adopting energy efficiency in buildings can serve as a possible and effective means of reducing energy consumption via real time monitoring, control and management (Kailas, Cecchi and Mukherjee 2012). Besides, it helps in reducing energy wastage as well as heightening the energy conservation potentials of buildings particularly during the peak periods. Moreover, buildings that are energy-efficient will benefit from decreased long-term expenses for energy consumption, water use, maintenance and so on. Thus, by reducing operational costs, the original investment in energy-efficient buildings measures can be regained while worth and marketability can both increase.

#### ***2.6.1.2 Minimizes environmental impacts and climate change mitigation***

Buildings that are energy efficient could invariably produce fewer carbon emissions because they utilize fewer or no fossil fuels. For example, the lowest emissions are found in buildings that predominantly employ renewable energy, such as hydroelectricity (Chel and Kaushik 2018). Likewise, buildings that use less energy also use less water, produce less waste, and pollute less air, all of which can benefit both the ecosystem and people's well-being (Wuni, Shen and Osei-Kyei 2019). Thereby, the environmental balance can be improved significantly.

#### ***2.6.1.3 Enhances users' comfort and productivity***

By ensuring ideal levels of lighting, air quality, temperature and humidity, occupants can have a more comfortable and healthful indoor environment resulting from energy-efficient buildings. In

specifics, buildings that utilize less energy in residential, educational, or workplace environments can enhance inhabitants' well-being, contentment, and optimal performance.

#### ***2.6.1.4 Serves as a building block for smart buildings***

With the ongoing evolution in advanced technology, modern buildings will require multifaceted strategies that can provide comfortable conditions to occupants in an energy-efficient manner. In this light, the management of energy-efficient systems in new and existing buildings can be extended to incorporate monitoring, control and interactions with other smart building services and devices such as smart lighting solutions (Agbajor *et al.* 2023). Additionally, large scale acquisition of data is feasible via a modern building energy management system (BEMS). Using a networked solution means that data can be shared throughout the building and consequently, the BEMS data can be fed directly into other systems and can be used to determine proactive planned preventive maintenance.

#### ***2.6.1.5 Improves security and resilience***

Generally, by employing fewer external energy sources and having alternative systems in place, energy-efficient buildings can be less vulnerable to exogenous shocks like power outages, adverse weather conditions, or price changes. Moreover, by decreasing the need for imported fossil fuels, energy-efficient edifices can help improve the security of the energy supply.

### **2.6.2. Greenery-based energy-saving systems for green building**

#### ***2.6.2.1 Green roof systems***

As an energy-saving greenery system, green roofs are topped vegetative components with growth media which are also referred to as living roofs or roof gardening (Vijayaraghavan 2016). According to research, the design and construction of green roofs is a practical strategy for resilient, sustainable, healthy, and habitable built environments, which are encouraged by urban environmental concerns (Zhang and He 2021). In other words, green roofs provide dual purposes of improving building's aesthetics and people's health while simultaneously reducing the influence that humans have on the environment. Besides, numerous benefits such as runoff control, prolonged roof longevity, air purification, sound insulation property value, energy efficiency, among others, can be achieved when green roofs are properly put in place (Vijayaraghavan 2016). Figure 2.5 presents practical application of these greenery systems while extant studies revealed that that green roofs via rooftops can reduce indoor temperature by about 8°C, cooling loads by 60% and summer heat transmission by about 80% (Besir and Cuce 2018; Abuseif, Dupre and Michael 2021). Moreover, novel advances in technology have indicated the integrated application

of green roofs with other energy-efficient measures. For example, Shafique, Luo and Zuo (2020) identified that photovoltaic (PV)-green roofs in comparison to traditional green roofs, offer significant advantages for the production of renewable electricity in green buildings. Also, Lai *et al.* (2023) mentioned that modular planting roof system is another innovative technology that can lower construction expenses and support the realization of green cities.

However, while market demand and high-tech innovation constitute the major drivers to green roof adoption, Zhang and He (2021) identified that inadequate governmental policy, people's apathy and unsound economic merits constitute the chief constraints in its implantation. Additionally, to determine the thermal performance of green roofs, Abuseif, Dupre and Michael (2021) suggested the necessity to consider their viability especially in hot desert regions like Qatar if the goal of minimizing energy usage will be achieved in such locations. This resonates the research by Shafique, Luo and Zuo (2020) affirming that the performance of green roof varies with building typology and urban density, thus illustrating the need to specify the ideal green roof layouts in future green building development and smart cities' models. In a nutshell, green roofs implementation in green buildings forms a sure avenue for built environment to adopt nature-based solutions in the transition towards carbon neutrality.



**Figure 2.5:** Nanyang Technological University's green roof in Singapore (Lai et al. 2023)

### 2.6.2.2 Vertical greenery systems

On the whole, the vertical greenery system (VGS) is a method for allowing various plant species to grow on building facades, whether they are man-made or naturally occurring, within or outside of a building (Loh 2008). VGSs can be categorized as intensive and extensive systems based on implementation criteria and operation cost and they are broadly classified as green facades and living walls (Pérez *et al.* 2014; Cuce *et al.* 2021). As pointed out by Pérez *et al.* (2014) the building's facade, including the internal and external walls, alongside the building's railings, serves as the bearer in a vertical greenery system. Essentially, in metropolitan areas where city growth has deposited green space and the urban heat island has become a major issue, Bustami *et al.* (2018) mentioned that the integration of VGSs can provide passive cooling and enhance sustainable development initiatives in most public buildings and spaces. The research by Lee and Jim (2017) identified that installing VGS on walls with more solar irradiance resulted in the greatest cooling advantages in sub-tropical regions. With regards to the natural environment, Pan and Chu (2016) investigated the ecological effects of VGSs. Their findings identified that VGSs achieved 16% annual energy savings during summer months while a total of 43–97% of the environmental effect categories were positively influenced by VGSs. However, Bustami *et al.* (2018) clearly stated that focusing solely on VGS's thermal advantages for the building runs the danger of neglecting VGS's entire potential. Moreover, it is imperative to consider all intrinsic costs and upkeep for green walls from the beginning as a long-term project.

In this modern day, it is crucial that buildings and cities operate well in terms of energy and the environment. Thus, some studies identified living walls (LVs) to substantially mitigate environmental pollution in megacities with potent capacity to lower building energy use and capture CO<sub>2</sub> (Charoenkit and Yiemwattana 2016; Chen, Ding and Liu 2019). Actually, LVs can drastically decrease the absorbed heat flux into the building, thus reducing the amount of energy needed for cooling or heating. Applicably, LVs can be installed in continuous form or modular form while the former offers more advanced solutions than the latter in terms of climate mitigation (Manso and Castro-Gomes 2015). Meanwhile, Safikhani and Baharvand (2017) stressed that the diversity of utilized LVs materials, optimum distance between building fabric and LVs, as well as installed LVs in different building orientations are essential aspects requiring consideration. According to them, this will not only improve the indoor thermal conditions of LVs but also boost the performance efficiency of green buildings.

Summarily, it could be implied that VGSs offer great energy-saving potential and is environmentally sustainable. Green facades could be emphasized for building fabrics that receive more direct sunlight while LVs is a promising measure for climate change vindication when duly

installed in green buildings.

### **2.6.3. Renewable energy technologies for energy-saving in green building**

Undoubtedly, the utilization of renewable energy in buildings is imperative to actualize the lofty target of carbon neutrality on or before 2060. By and large, solar, wind and geothermal energy systems are found as the major renewable energy sources for green buildings. They can be integrated lonely or as a hybrid into buildings to achieve more energy performance and saving. Details on these energy sources are elucidated below.

#### ***2.6.3.1 Building-integrated wind energy systems***

Wind energy is known to be a well-developed source of renewable energy which is abundant and neat. From an environmental standpoint, wind energy does not emit greenhouse gases or release atmospheric pollutants. With respect to the geometry of the building, Lin, Chen and Tsay (2021) affirmed that wind energy setting and evaluation of thermal comfort can improve green building energy efficiency alongside occupants' comfort and wellness. According to Lai *et al.* (2023), it was discovered that this energy type is mostly prevalent in monsoon regions and best fitted for buildings whose design and construction adopt it as an alternative and renewable energy source. In application, wind turbines are commonest types of available wind energy source for buildings. For instance, the study conducted by Li, Shu and Chen (2016) evaluated the viability of high-rise buildings integrated with wind turbine. Their research duly assessed the anticipated yearly and monthly power output wind turbines and found that they have significant energy-saving potential for windy regions and aerodynamic buildings. Also, an exploratory research by Lai *et al.* (2023) indicated that wind energy can be an ideal solution for ecofriendly buildings along coastline areas like Vietnam with an average wind speed ranging from 5.5 m/s to 7.3 m/s, having abundant wind resources over the year.

Meanwhile, only few studies have considered this renewable energy source despite its significance. Utilizing wind energy has volatility as its major drawback. More so, it is rarely completely available and sufficient for a particular place, and the usage rate varies significantly.

#### ***2.6.3.2 Building-integrated solar energy systems***

Solar energy is famed to be the most abundant renewable energy source provided by nature. Ideally, green buildings can save their heating and cooling expenses by using solar energy to heat them in the winter and shade them in the summer. According to Chen *et al.* (2022b) photothermal and photoelectric solar energy conversion methods are the most often used in buildings with the former offering more benefits in terms of improved energy performance and optimized lifecycle

cost. Broadly speaking, typical solar energy technologies such as solar water heaters, solar ventilation systems, solar shading systems, photovoltaic thermal (PVT) systems, and solar absorption refrigeration systems are well reported by researchers as the mostly incorporated approaches in buildings (Siecker, Kusakana and Numbi 2017; Zain Ahmed *et al.* 2021; Martín-Chivelet *et al.* 2022; Agbajor, Mewomo and Mogaji 2023). PVTs for example, are hybrid systems comprising photovoltaic and solar thermal components that transform incident solar irradiation to simultaneously produce electrical power and heat energy with enhanced energy efficiency in buildings (Yu *et al.* 2021). Jeong *et al.* (2018) pointed out that PVTs are an attractive advancement in solar technology that improves the dual roles of energy conversion efficiency and economically utilizing spaces in buildings to form building integrated photovoltaic (BIPV) systems. Happle *et al.* (2019) opined that BIPV has advanced quickly and has the potential to lessen building operational carbon emissions by up to 50% in regions like Southeast Asia. Similarly, recent study by Taşer, Koyunbaba and Kazanasmaz (2023) indicated that adopting BIPV technology helps to provide better daylight, thermal comfort and energy-saving potentials of buildings while constituting a sustainable future for cities. However, it was revealed by Samarasinghalage *et al.* (2022) that designing BIPV systems requires the consideration of a sizable number of PVTs and envelope-related features as well as competing performance standards.

In the meantime, applying solar ventilation technologies like solar chimneys, induced ventilation wind traps were unveiled as strategic approaches that offer good indoor condition for building occupants (Utama, Fathoni and Kristianto 2014; Hall and Allen 2015). Where solar energy is abundant, Haghghi and Maerefat (2014) mentioned that solar chimney is an excellent structure that can be used in green buildings to achieve natural ventilation in regions having cooler temperatures and locations where a small amount of indoor variation is reasonable. In hot and humid tropical regions, a case evidence is the exploratory study by Tan and Wong (2012) where a classroom was connected with a solar chimney system. Their findings revealed that during a one to two-hour positive temperature lag, the optimum indoor air speed of 0.49 m/s was attained with improved indoor air speed whenever the chimney's inlet is lowered. In another vein, analytical findings from research conducted by Bukoski *et al.* (2014); Alhamid *et al.* (2020); Mat Wajid *et al.* (2021) identified solar absorption refrigeration as a promising technique when installed in green envelopes as it helps to guarantee acceptable thermal comfort, optimized energy performance and offer positive ecological advantages.

### **2.6.3.3 Building-integrated geothermal energy systems**

In brief, geothermal energy is the energy derived from the internal heat of the Earth. According

to D'Agostino *et al.* (2022), it is the second-most important renewable energy source on the planet after solar energy and the enthalpy of geothermal energy plants can be classified as low, medium, or high depending on the earth's ambient temperature. With regards to green buildings, Pinto, Rodrigues and Mota (2017) reported that geothermal systems are particularly attractive in Europe's northern and eastern regions since they can reduce energy requirements for HVAC systems in buildings by 25–75%. Meanwhile, Sang *et al.* (2022) indicated that a type of energy-saving device known as ground source heat pump (GSHP) is the dominant geothermal system which uses the soil's subterranean temperature storage to generate heat and cool the building interior. For instance, it is a renewable energy technique employed by the Italian government as a retrofitting strategy to attain the net zero energy buildings (NZEB) initiative (D'Agostino *et al.* 2022). In this modern era where the assessment, monitoring, and reduction of heating and cooling energy use are becoming increasingly important for buildings, Francesco *et al.* (2016) mentioned that winter heating can be provided through GSHPs which transfer heat from a source into buildings, while the procedure can be swapped around in the summer so that the heat pump removes heat from buildings and releases it into the earth. In mainland Portugal where most typical ground temperature ranges from 20°C to 40°C, an investigation conducted by Pinto, Rodrigues and Mota (2017) identified that GSHP helps to achieve 34% of annual primary energy savings in a case university building. Similarly, results from numerical simulation study by Widiatmojo *et al.* (2021) inferred that the demand for electrical power during hotter times can be significantly reduced by using geothermal energy for cooling buildings in Thailand.

In all, it can be deduced that applying geothermal systems are beneficial to building envelopes in terms of renewable energy generation, primary energy savings and carbon emission reduction. Also, they offer dual merits of being used in summer and winter periods. The core challenge is evident in how to enhance its yearly usage in regions like sub-Saharan Africa and South America where this energy source is sparsely applied.

## **2.6.4 Energy-saving methods for green building envelope**

### ***2.6.4.1 Passive roof-top cooling***

The rooftop serves as the building envelope which has direct contact with the sun where intense solar radiation is being absorbed. Moreover, it absorbs a sizable amount of solar radiation at daytime and conducts a sizable portion of this heat to the building interior, thus causing significantly overheating of indoor spaces (Kadri, Bouchair and Laafer 2022). Owing to roof's specific location, components and shape, Tong and Li (2017) pointed out that in clear sky conditions, direct solar irradiance can attain nearly 1000 W/m<sup>2</sup> on the roof, which is most exposed

to solar radiation. However, from numerous exploratory studies and real-world practical adoption, several energy-saving strategies in form of radiative roof cooling techniques are employed to bolster energy efficiency in buildings. Ideally, these techniques can be delineated on both flat surfaces and pitched roof coverings, and according to Tong and Li (2017), most of these strategies are deployed on rooftops during summer periods or in tropical regions in order to lower the building's air-conditioning demand. This indicates that the energy consumption reduction and energy-saving pattern in building roofs is location-specific and dependent on seasonal variations. Instances account how energy consumption modelling and simulation for green roofs performed on low-rise buildings resulted in substantially yearly baseline heating and cooling load energy savings above 12% across Iran's three different climatic locations (Ebadati and Ehyaei 2020). Also, adopting cool roof (having solar reflectance and high thermal emittance properties) to reduce heat absorption into buildings is a common passive cooling strategy. Since cool roofs comprise surfaces that reflect heat and sunshine away from the building, they provide promising potentials that can drastically cut cooling expenses (Zingre *et al.* 2015). Similarly, double-skin roof is another passive energy-saving cooling method for green building envelopes. This is because double-skin roofs contain two solid roofs – a secondary roof above and a primary roof beneath separated by an aperture, with the former protecting the latter from incident solar irradiance while the aperture provides insulation and heat flux entry (Zingre *et al.* 2015). Applicably, these roof-cooling mechanisms have been ideal green cooling solutions mostly in hot and arid regions such as Algeria and Djibouti (Omar *et al.* 2017; Kadri, Bouchair and Laafer 2022).

Additionally, Lai *et al.* (2023) vividly opined that in order to reduce cooling demand in subtropical and tropical zones, several other sustainable roof cooling techniques like reflective and mass insulation, cool-colour roofs, ventilated roof and such like, should be utilized. Also, to ameliorate ultraviolet irradiance effect on roof surfaces, Sadineni, Madala and Boehm (2011) emphasized roof coatings as another proven strategy although the preferred chosen roof coating is usually dependent on high solar reflectance and high emissivity during the day and night respectively. For instance, the heat flux of a white concrete roof can be lowered by 4 °C on a sunny summer day and by 2 °C at night by utilizing cool coatings which is more appealing than aluminium coating having low thermal emittance (Sadineni, Madala and Boehm 2011). Besides the aforesaid strategies, other prominent approaches unveiled from literature comprise economic roof shading, compact cellular roof layout, white-washed exterior roof surfaces, vegetative roof, ventilated roofs, vaulted roofs, and whatnot (Permpituck and Namprakai 2012; Lee *et al.* 2017; Yew *et al.* 2018). Nicely, these strategies offer diverse features like little sunlight exposure,

lowering solar absorptivity, humidification, and coverage, among others (Sangkakool *et al.* 2018; Yang *et al.* 2018). From the highlighted survey, it could be inferred that the emergence and application of these diverse roof systems can be influenced by modification on building location and climatic conditions, especially in tropical zones. Arguably, there are very few studies on energy-saving roof cooling techniques for other climatic regions such as cold and coastal regions (like south-eastern South Africa) which have their own peculiarities.

#### **2.6.4.2 Passive wall systems**

Generally, walls constitute the building's envelope outermost element and major component with high surface area. They serve as passageway for heat flux transfer of incident solar radiation from the sun to the building interior and also offer a sizable surface that helps with thermal radiation in cold regions (Lai *et al.* 2023). This makes the operational energy demand by the building's indoor environment to be very high. Based on geographical region and material availability, most walls are usually made of stone, brick, timber, steel or concrete while the ability of each material to withstand solar radiation depends on its thermal properties (Bojić, Johannes and Kuznik 2014).

However, according to Omrany *et al.* (2016), improved thermal and energy performance of walls is a key strategy for reducing the energy use of the building's indoor environment. Meanwhile, archival literature overviews illustrate how a plethora of energy-efficient walls can facilitate the adoption of green building envelopes. Ideally, several scholars have researched the strategic potentials of passive walls systems such as green walls, double skin walls, trombe walls, composite walls, and autoclaved aerated concrete walls, while their resultant findings showed improved energy-savings attained via these systems. For example, installing trombe walls in green building envelope is inexpensive, reduces moisture and energy consumption, offers improved thermal comfort of interior and adjoining spaces and is suitable for humid regions (Saadatian *et al.* 2012). The research by Bojić, Johannes and Kuznik (2014) typically applied the trombe wall system to investigate the optimal energy and ecological performance of case buildings in France which yielded an annual energy saving of 20%. In the meantime, green walls help to alleviate indoor heat gains and losses, enhance building aesthetics and acoustics properties and can be employed for green retrofits (Van Renterghem *et al.* 2013). As illustrated by Manso and Castro-Gomes (2015), the variant construction attributes of green walls has aided its practical adoption, thereby propelling its prominence majorly in developed regions like Germany, Hong Kong and Singapore (Yuen and Nyuk Hien 2005). Wong and Baldwin (2016) presented a real case study whereby green walls reduced a multistorey residential building's cooling load in Hong Kong while achieving a 64% yearly energy saving. Furthermore, autoclaved aerated concrete

walls are reported to provide ecofriendliness, fire resistance, lower density and thermal conductivity than normal concrete, thus enabling their usage as a green masonry material (Bisceglie, Gigante and Bergonzoni 2014; Kunchariyakun, Asavapisit and Sombatsompop 2015). According to established models and validation results from Lei, Yang and Yang (2016) research, phase change materials (PCMs) have a notable advantage in the tropics over other locations due to their year-round use.

Overall, passive wall systems offer ideal solutions for achieving high-performance buildings in this current era. Nonetheless, Kubota and Zakaria (2019) pinpointed that the long-term efficacy of the thermal insulation properties of materials used in passive wall systems generates some challenges due to the current rapid climatic changes. The energy needed to building heating and cooling can be greatly reduced by carefully considering proper insulation of walls across the world's numerous climate zones (Lai *et al.* 2023). Fiberglass, spray foam, and cellulose are prominent examples of insulation materials with high R-values (resistance to heat flow) (Woltman, Noel and Fam 2017).

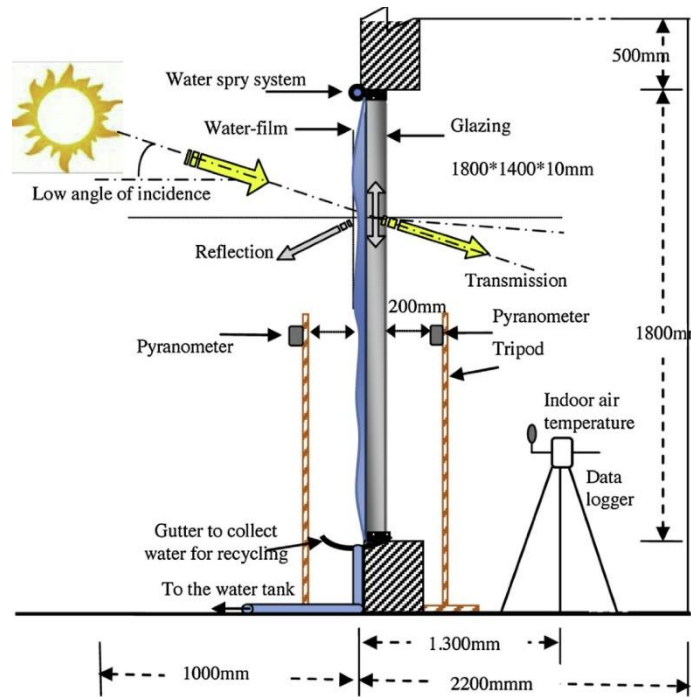
#### ***2.6.4.3 Energy-efficient windows***

In terms of green buildings' interior energy performance, the window system is typically viewed as the most susceptible building envelope component. Thus, buildings have become increasingly designed with big glazing sections to obtain a pleasant exterior view and receive enough daylight (Yao and Zheng 2017). However, an investigative study by Yao and Xu (2010) revealed that the solar energy gain via windows is 20 times greater in summer than through the adjoining walls, thereby constituting unfavourable effects such as considerable increases in cooling costs and overheating issues. Since glass constitutes the major part of most windows, Lai *et al.* (2023) affirmed that the effectiveness of solar heat transfer and internal heat gain in buildings are substantially influenced by the glass's illuminance and thermal properties. Also, some extant studies inferred that the heat transfer coefficient (U value) of a window is the primary factor that determines its thermal performance (Azis 2021; Himmetoğlu *et al.* 2022). Notably, strategic approaches such as multiple glazing, low-emissivity coatings, tight sealing, dynamic tinting, insulation, and whatnot, were highlighted by scholars as proven techniques for enhancing optimal thermal performance of windows (Wheeler *et al.* 2022; Akram *et al.* 2023).

In specifics, double or triple glazed windows have an established and widely used energy-saving ability to conserve thermal energy especially in cold climates. An experimental study conducted by Lau *et al.* (2016) concluded that an increased annual cooling energy savings around 10% can be achieved when double-glazed facades are applied to high-rise commercial buildings in

Malaysia. Similarly, the performance of double glazing for green building retrofit was demonstrated by Ihara *et al.* (2015) in Singapore, where transparent glass placed for tropical conditions can save up to 4% annually on energy costs, while tinted glass installed for similar climates can save up to 7.5% annually. Moreover, it was revealed that single-glazed windows can be replaced with double-glazed windows to save between 39 and 53% energy, according to UK research on energy efficiency in commercial buildings (Mortimer *et al.* 1998). Meanwhile, the utilization of low-emissivity glass with unique coatings can help to reflect heat back into the space, minimizing heat absorption and loss in the summer and winter. For instance, the study reported by Ihara *et al.* (2015) concluded that aerogel granulate glazing systems could provide a solution in hot and mild climates in addition to cold climates from the viewpoint of building energy-saving. Likewise, the results of a simulation study by Pawar, Boranian and Lang (2019) showed that low-E film reduced the U-value and solar heat gain coefficient by 13% and 1%, respectively.

In another scenario, applying thin water films in buildings is another efficacious energy saving strategy. For instance, in a typical tropical region, Qahtan, Rao and Keumala (2014) researched that the sustainable glazed water film for buildings serves as a less expensive option to selective glazing as shown in Figure 2.6. Nowadays, dynamic glazing approaches that incorporate optical switching devices like thermotropics, suspended particles, polymer dispersed liquid crystals and chromogenic technologies are typically applied for energy conservation in buildings (Hee *et al.* 2015; Hemaïda *et al.* 2021). According to Bui *et al.* (2021), electrochromic windows are arguably the most implemented glazing technology in the current decade due to their capacity to change their aesthetics and thermal properties. From the authors' case study analysis, building energy consumption was reduced by an average of 16.4% when electrochromic windows are integrated in typical office buildings.



**Figure 2.6:** Energy-efficient glazed windows (Qahtan, Rao and Keumala 2014)

Summarily, it is evident that energy windows do not only enhance energy saving in buildings but also help to increase comfort, improve indoor air quality, and reduce annual energy costs. However, it is essential to carefully consider some major factors like overall building design, window orientation, and local climate in the selection of energy-efficient windows for optimal green building performance (Hee *et al.* 2015; He *et al.* 2019).

#### 2.6.4.4 Shading of building envelope

Building envelope shading offer intense benefits, such as lowering interior temperatures and consuming less energy for cooling. Broadly speaking, numerous shading devices can be applied in diverse case scenarios, the main ones including energy performance, daylight performance, and indoor comfort performance (De Luca, Sepúlveda and Varjas 2022). Promisingly, these systems can be applied to achieve either a single objective or integrated multi-criteria performance objectives. Applicably these envelope shading strategies were duly adopted in Brazil (Krüger and Zannin 2004); Canada (Berardi and Anaraki 2016), South Korea (Cho, Yoo and Kim 2014), Spain, Portugal, Egypt (Palmero-Marrero and Oliveira 2010). However, to avoid an uncomfortable indoor climate and an increase in cooling energy load, Al-Tamimi and Fadzil (2011) argued that it is crucial to have an ideal shading device before applying any of these approaches on rooftops, passive walls and energy-efficient windows. For instance, the research conducted by Lau *et al.* (2016) concluded that using shading devices rather than high performance glass in hot and humid climates will result in greater energy savings for cooling. Recent research

revealed that the length or depth of shading devices can significantly improve green building energy efficiency. In Malaysia, Al-Tamimi and Fadzil (2012) investigated the performance efficiency of envelope shading systems. Their findings indicated that the length of the shadow period applied in multistorey residential apartments resulted in greater annual load and peak load savings. Similar approach was employed in Singapore from the research of Wong and Li (2007). Their results evidently demonstrated that the building energy's cooling load can be reduced by 2.62–3.24 %, 5.85– 7.06 % and 8.27–10.13 % when horizontal shading devices are at depths of 30cm, 60cm and 90cm respectively.

Besides, static shading devices are new envelope shading technology that is commonly reported and well implemented in zero-carbon buildings (Kontadakis *et al.* 2017). More importantly, De Luca, Sepúlveda and Varjas (2022) illustrated that exterior static shading systems will not only manage sunshine and daylight to lessen glare but also maintain natural illumination and connection with the natural environment, thereby improving the mental and physical wellness of building occupants. Meanwhile, self-shading is another notable strategy for achieving energy-efficiency in buildings. According to the field experimental study by Kandar *et al.* (2019), the application of inclined wall self-shading approach at projection of 45% and inclination angle of 45° in buildings will result in less heat gain, which always results in less energy used for cooling. An ideal representation of self-shading device is seen in demonstrated in the construction of Holiday Inn Hotel in Singapore as shown in Figure 2.7 with its design based on the insolation analysis principle (Bruehlisauer *et al.* 2013).

In brief, it could be surmised that the geometry of external shade on buildings significantly lowers the amount of energy needed for cooling. As solar radiation absorption mostly affects the building's interior environment, proper application of ideal shading systems is vital to control the solar radiation in a substantial manner. Methods such static shading, self-shading devices are suitable means of achieving this and can be implemented in both hot and sunny climates as well as cooler regions. However, while these methods have gained grounds and well renowned in Asia, Europe, and North America, they are sparingly adopted in Africa setting.



**Figure 2.7:** Holiday Inn Hotel in Singapore (Lai et al. 2023)

## **2.7. Optimization Approaches for Energy Efficiency in Green Buildings**

Broadly speaking, the green building façade is a crucial element of the sustainable building designs that governments have adopted to cut down on both greenhouse gases emissions and energy use. When considering thermal energy use, the environment, and comfortable indoor standards, Himmetoğlu *et al.* (2022) affirmed that green façades hold the largest proportion. However, in real world applications, the creation of green building envelopes that are feasible for energy reduction is a serious optimization challenge in view of multicriteria factors including design, performance, control, and such like, being considered by project participants and decision makers (Yang *et al.* 2017).

Besides the passive methods highlighted in the preceding section, Gan *et al.* (2020b) technological advancement have aided the utilization of robust optimization methods to enhance green building performance from a lifecycle perspective. According to Wang *et al.* (2023), optimizing energy use while preserving occupants' comfort levels is one of the primary difficulties of green building energy optimization systems. In this light, this section examines the various optimization techniques their applications in green building energy efficiency as it sparked increased interest among scholars. With regards to green building, these optimization methods are generally categorized as classical, metaheuristics and data-driven/machine learning approaches (Kheiri 2018; Gan *et al.* 2020b; Wang *et al.* 2023).

### 2.7.1 Classical mathematical optimization techniques

Overall, classical mathematical optimization methods employ sets of computations and functional connections as the objective and constraints. According to Alabi *et al.* (2022), the suitable objective function to be optimized, the constraints on the application scenario, and the bounds of the decision variables are specified in the formulation of the problem. In the context of energy efficiency in green buildings, Gan *et al.* (2019) asserted that the approach involves developing a proposed method via mathematical programming along with simulation tools for the design and operation of high-performance buildings. In this case, the specified constraints can either be nonlinear or linear while single- or multi-objective objective functions are possible (Lin *et al.* 2021). Generally, classical optimization methods mainly include linear programming (LP), mixed-integer linear programming (MILP), non-linear programming (NLP) and multi-objective programming (Zhou and Zhou 2021).

For LP, Alabi *et al.* (2022) mentioned that the objective is a linear function, the variables are linear in nature, and the constraints on the problem formulation having a linear relationship. An experimental study by Privitera *et al.* (2011) adopted an LP model called CARB-OPT to reduce the installation costs of renewable energy systems (RES) for buildings. It was inferred that utilizing LP to practically analyze initial viability for renewables in buildings can be a highly effective technique for selecting the best technology combination. Similarly, Savolainen and Lahdelma (2022) applied the LP model based on a 15-minute power balance settlement to optimize the operation of hybrid RES for buildings. The optimized LP models achieved substantial yearly energy cost savings for some selected buildings in Finland while lowering the consumption of non-renewable primary energy. Within the scope of sustainable buildings, LP models have likewise been utilized to improve the design of building energy conservation (Chang *et al.*, 2011), enhance building energy schedule (Georgiou, Christodoulides and Kalogirou 2020), solve techno-economic issues of high-performance buildings (Gupta, Anand and Gupta 2017), and such like. In sum, LP offers flexible scheduling and coding simplicity, making it an expansive and powerful decision-making method, which provides some strategic solutions that can improve green building energy efficiency. Yet, it is restricted to situations where the relationships between integrated systems may be described by linear functions (Alabi *et al.* 2022).

Meanwhile, MILP is used in building energy optimization to solve binary variables issues by integrating categorical and continual mathematical modelling methods (Urbanucci 2018). For instance, the research conducted by Motalebi, Rashidi and Nasiri (2022) concluded that the optimal solution for retrofitting buildings for energy efficiency can be formulated via the MILP model Kotzur *et al.* (2020) introduced the MILP for future-optimized the energy supply prediction of selected

housing units in Germany to achieve the cost-optimal technology utilization and operation. Li (2018) applied the MILP model to find an approach for running energy hubs in commercial buildings. The model achieved an equilibrium between the operation expenses and occupants' comfort level in commercial buildings under varied temperature deviations. A multicriteria MILP approach was employed by Bucoń and Czarnigowska (2021) for the post-occupancy evaluation and desired performance level of building stocks. Its ease makes it a useful tool for making extended maintenance plans for residential apartments and reducing maintenance costs. In short, the MILP approach has generally been used to address a variety of computation complexity, mainly those with many decision variables, with cost reductions as the most prevalent objective function (Alabi *et al.* 2022). Since its dependent variables are restricted to having integer values, Chiam *et al.* (2022) asserted that it guarantees global optimality and minimal repetitions during energy-efficient building simulations.

Basically, the NLP optimization technique is appropriate in situations where the objective functions and constraints constitute nonlinear parts (Zhou and Zhou 2021). There are very few studies on the application of NLP for optimal performance of green buildings. Earlier studies adopted the Simplex method which is practicably quite effective and converges in anticipated polynomial time. These studies addressed relevant nonlinear objectives to be mainly economic, environmental or energy-related functions that are subjected to nonlinear constraints such as energy balance, energy demand loads in buildings, among others. For instance, Fokaides *et al.* (2017) employed the NLP's simplex algorithm to determine the ideal design configuration of a building shell based on optimizing its solar exposure varying weather situations. Fan *et al.* (2022) introduced the NLP approach to achieve cost optimization and ultimate building energy efficiency. The NLP solver was applied by Jemaa, Kotman and Graichen (2018) to evaluate the energy-saving potential of demand control ventilation systems in buildings based on carbon emissions. Their results indicated that the NLP solver enabled optimal HVAC system operation with energy use reduction and occupants' comfort maximization. However, it is worth mentioning that the NLP approach works with more iterations although it permits the solution of complicated problems with straightforward processes (Zhou and Zhou 2021).

### **2.7.2 Metaheuristic optimization methods**

The expanding intricacies and diversities of optimizing energy-efficient green building systems have made classical approaches obsolete due to their inability to provide the best results within a short time. Thus, energy-efficient green buildings can be designed and optimized for higher performance via a class of optimization techniques known as *metaheuristics* (Wang *et al.* 2023). In other words, metaheuristic algorithms are used to solve nonlinear or continuous optimization issues regarding ecofriendly buildings since they are more precise, effective, and able to produce ideal results.

However, among diverse groupings of metaheuristics identified in extant related works (Nanda and Panda 2014; Zhou and Zhou 2021), recent studies by Alabi *et al.* (2022) and Li *et al.* (2023b) affirmed that scientific classification is mostly preferred to reflect the nature and application of these optimization algorithms which imitate some biology, sociology, physics and mathematics-based principles. Meanwhile, in real-world design, performance, control and prediction of energy-efficient green buildings, Kheiri (2018) identified the prominent algorithms duly employed comprise genetic algorithm (GA), particle swarm optimization (PSO), ant colony optimization (ACO) and simulated annealing (SA).

In general, GA is a population-based optimization algorithm motivated by natural selection and genetics principles predicated on passing on healthy genes from one generation to the following would result in the fittest possible population (Himmetoğlu *et al.* 2022). Applicably, it can be utilized to optimize different aspects of a building's design, including the envelope geometry, orientation, shading, and HVAC system, in order to limit energy use and the building's environmental effect (Costa-Carrapiço, Raslan and González 2020). For instance, Gan *et al.* (2019) developed an evolutionary GA method to identify the best layout plan that maximizes energy efficiency in high-rise buildings. Using a 40-storey building in Hong Kong as a case study, their findings indicated that GA enables the optimal use of natural-occurring energy sources to minimize total energy consumption by 30-40%. Similarly, Sun, Luo and Liu (2021) developed a GA-based building control virtual testbed to improve the academic schedules in a case university taking building energy efficiency into account. The deployed optimization strategy recorded about 4% energy savings during an autumn semester.

Meanwhile, PSO is a swarm intelligence approach used to solve complicated problems at the best possible level. According to Kaveh (2014), streamlined social models involving the concepts of swarming, fish schooling, bird flocking and allied artificial life served as the basis for PSO. It is a potent optimization technique vastly employed to design energy-efficient building fabric along with the evaluation of building performance. As a case evidence, Carlucci, Pagliano and Zangheri (2013) employed the PSO with such simulation tools as GenOpt and EnergyPlus, to assess and optimize the performance and passive strategies of a residential building envelope respectively. An experimental study by Maria *et al.* (2015) combined PSO with GenOpt and TRNSYS software to lower a classroom's overall energy demand for lighting, heating and cooling. PSO have likewise been adopted to optimize a variety of green building design elements, including visual comfort and daylighting systems (Wagiman *et al.* 2021), HVAC systems (Chaturvedi *et al.* 2022), shading equipment and insulation thickness (Chen *et al.* 2019), to reduce energy use and enhance indoor air quality (Zhao *et al.* 2021). In sum, it could be inferred that PSO can be used to solve discrete problems including both

local and global optimal measures for building energy-saving and CO<sub>2</sub> emission reduction.

ACO is a probabilistic method that is developed after studying ant behaviour to find optimum solution to computational issues through graphs (Liao *et al.* 2014). Since it produces more accurate solutions, better consistent outcomes, and a quick convergence rate, Bamdad *et al.* (2017) affirmed that it is suitable for solving building energy optimization problems. Practically, some studies have identified different aspects where ACO have been introduced for green building energy performance evaluation as well as the future prediction of energy-optimized buildings. For example, Bamdad *et al.* (2017) applied the ACO for continuous domain to enhance the operation efficiency of a typical commercial building. The findings revealed that approach can still save more energy than 11.4% even after several conventional energy-saving techniques have been put in place. Similarly, Bamdad *et al.* (2021) introduced the ACO to compare the energy-optimized designs of two case buildings in two Australian cities with respect to the current and future climates. Also, Chen, Janssen and Schlueter (2018) employed the ACO to estimate realistic expenses and enhance building performance. Their findings revealed that sustainable buildings can operate efficiently via the developed ACO algorithm, with the conclusion that high-quality design plans for proposed green buildings can also be achieved.

Similarly, other metaheuristic algorithms like imperialist competitive algorithm (Wang *et al.* 2023), simulated annealing (Junghans and Darde 2015), grey wolf optimization (Chaturvedi and Elangovan 2023), and such like, have been applied to maximize energy savings in smart green buildings working inside smart grid architecture while considering the surrounding environment and energy demand patterns. More so, since the optimization of energy-efficient green buildings is a multidimensional approach, it is possible to integrate these metaheuristic techniques to achieve optimal results as delineated in studies like Junghans and Darde (2015) and Chaturvedi *et al.* (2022). To sum up, metaheuristics are helpful optimization tools for improving the design of zero energy buildings. Although they can result in substantial energy savings and enhanced building performance, developing the optimization algorithms technique is challenging and expensive to implement.

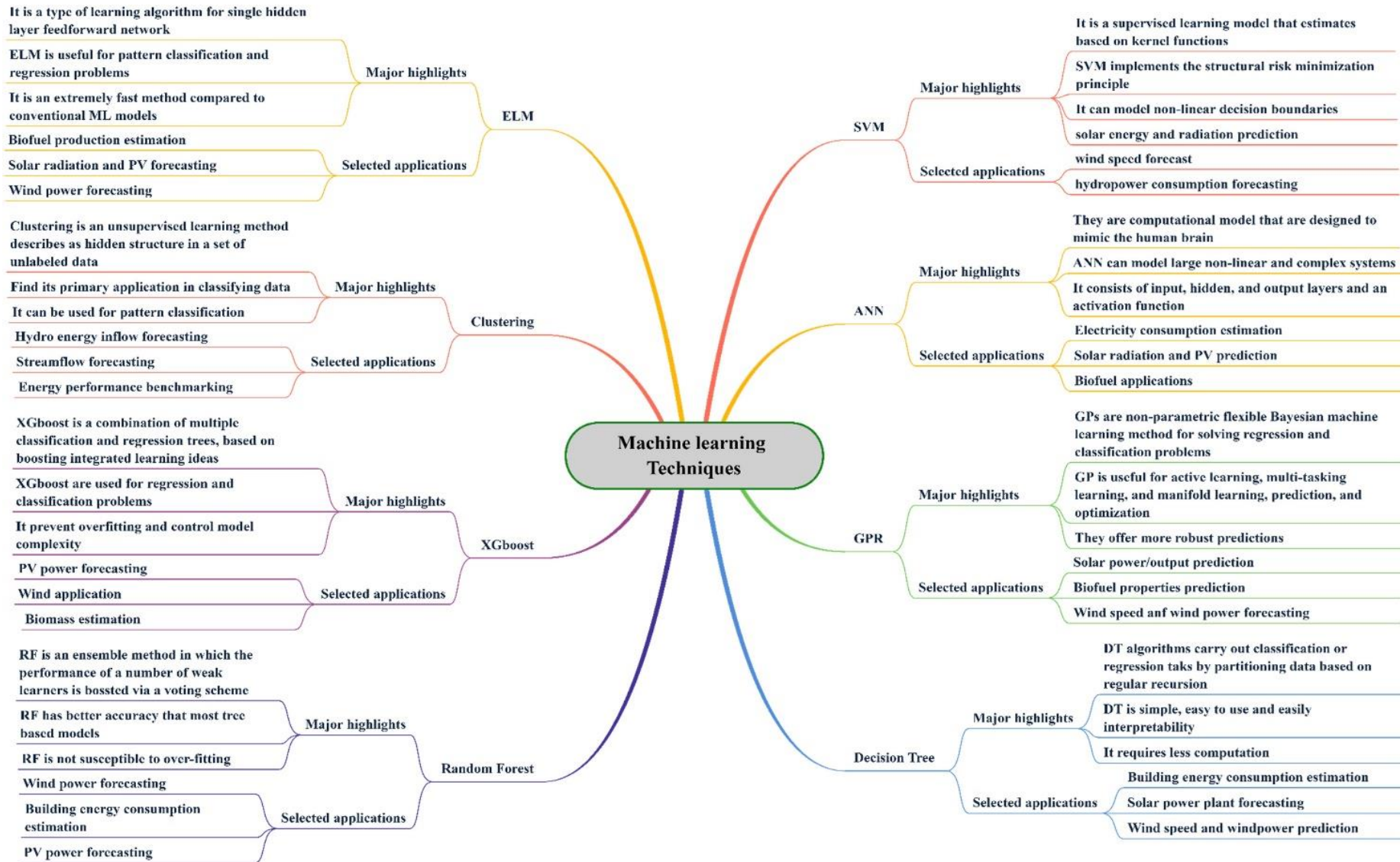
### **2.7.3. Data-driven (machine learning) optimization methods**

As green building energy system's intricacies increases, likely drawbacks in classical methods and metaheuristic algorithms may include a tendency to settle for local optimal solutions or a slow convergence rate (Zhou and Zhou 2021). However, with the current breakthroughs and surge in digital technology, Gan *et al.* (2020b) mentioned that data-driven techniques such as machine learning (ML) have become the most recent promising pathway to address building energy optimization complexities while achieving the multicriteria objectives for most typical building envelopes. Being an advanced computer algorithm, Alabi *et al.* (2022) described ML to learn from past data to forecast

future results, while the algorithms are broadly classified into supervised learning, unsupervised learning, and deep learning. Several studies have identified ML's potential to transform green buildings' operational performance by reducing energy use while it can help predict the best method of optimizing energy efficiency, user comfort, low carbon emission and life-cycle cost in buildings (Sun, Haghighat and Fung 2020; Verma, Prakash and Kumar 2020).

Meanwhile, a holistic survey on ML optimization approaches for green buildings indicates that diverse methods have been developed as regards the design, performance, control prediction, socio-economic and environmental sustainability of zero energy buildings. Generally, the mostly applied ML models comprise artificial neural network (ANN), support vector machine (SVM), ML linear regression, random forest, decision trees, Gaussian process regressors (GPR) and deep neural networks (DNN) (Sun, Haghighat and Fung 2020; Aghimien *et al.* 2023). The ANN is an ideal tool for identifying intricate relationships between input parameters like building envelope and climate variables and output elements like material cost, carbon emissions alongside heating and cooling energy usage (Himmetoğlu *et al.* 2022). Dong and Zhang (2023) utilized the ML linear regression to predict the ecological footprint of Hong Kong's buildings by 2050. Similarly, Mlangeni, Ezugwu and Chiroma (2020) applied the DNN to forecast energy consumption in university buildings, using energy datasets like ambient temperature, heating degree days, ambient relative humidity, and so on. Considering occupants' behaviour and comfort levels, Wang, Hu and Chen (2023) opined that these ML algorithms can adapt temperature, lighting, and other indoor environmental features to offer individualized comfort while reducing energy waste by learning about user attributes in buildings.

By and large, Figure 2.8 illustrates a pictorial overview of the major ML features in green building applications like estimating building energy use, wind speed forecast in buildings and such like. According to research, the identified ML models can be promisingly integrated especially when forecasting energy benchmarking for future energy-optimised buildings (Wang, Hu and Chen 2023) or they are combined with metaheuristic algorithms like GA and PSO for enhanced green building energy optimization (Himmetoğlu *et al.* 2022; Zhang *et al.* 2022). In sum, it could be inferred that data-driven optimization approaches are envisaged to play unique ever-increasingly significant roles in making green buildings more effective, sustainable, and comfortable for their occupants as modern technology keeps developing.



**Figure 2.8:** Machine learning approaches for energy-efficient green building optimization (Alabi et al. 2022)

## **2.8 Chapter Summary**

In this chapter, a detailed account of literature that encompasses worldwide energy and ecosystem with respect to climate change and sustainable development was provided. Attributes of the building industry and the need for sustainable construction were explored. Also, the chapter provided a comprehensive review on issues surrounding green building in the context of this research study. Furthermore, energy-saving action plans alongside optimization techniques for energy efficiency in green envelopes were discussed.

# CHAPTER 3

## Research Methodology

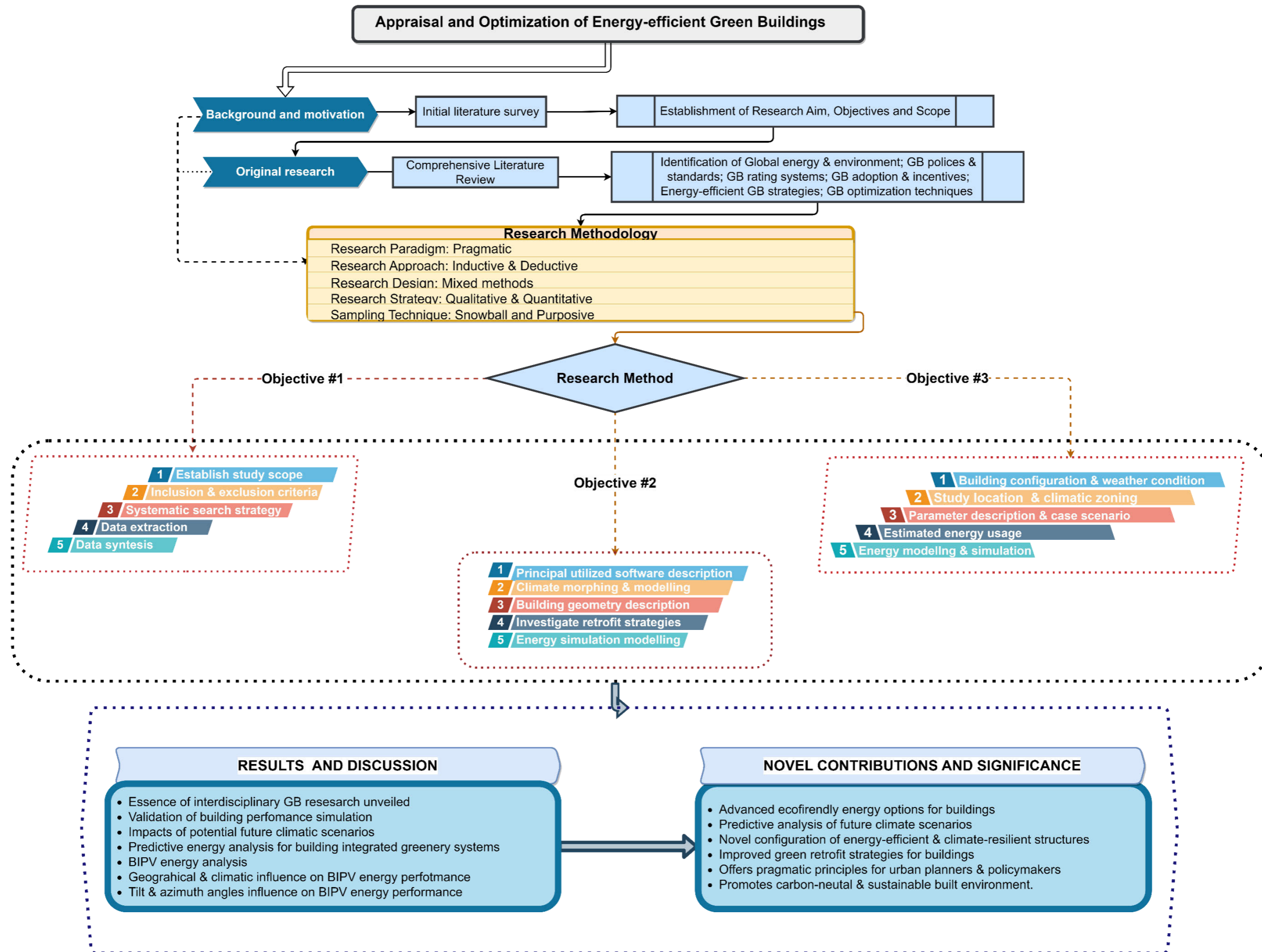
### 3.1. Chapter Overview

The aim of this chapter is to provide confidence and validation regarding the robustness of the study's methodology. It commences by elucidating the fundamental philosophy and rationale underpinning the study, followed by an exposition of the research methodology. This chapter also expounds on the steps taken to implement the research approach in order to accomplish the study's objectives. As shown in Figure 3.1, these encompass the research framework, approach, materials, data gathering techniques, analysis scope and methods used for data interpretation.

### 3.2. Research Philosophy

According to Kamal (2019), a key component of the research technique that supports the entire strategy and design of the study is research philosophy, which is often referred to as the philosophical viewpoint or paradigm by some other scholars. Muzari, Shava and Shonhiwa (2022) mentioned that it includes the researcher's presumptions on knowledge, reality, and their interaction with their research subject. By and large, in any typical research, the study design, data collection techniques, data processing, and ultimate findings interpretation are all influenced by the research philosophy that is chosen (Kaushik and Walsh 2019).

Generally, the main research philosophies include positivism, interpretivism, and pragmatism (Pham 2018). In the broad sense, the positivism school of thought in quantitative research holds that there is an objective reality that can be investigated without the involvement of the researcher (Alharahsheh and Pius 2020). With its roots in the scientific principles, Pham (2018) alluded that this research philosophy places a strong emphasis on observational evidence, measurement, and the application of logical reasoning. Apparently, this philosophical stance comprises features such as objectivity, hypothesis testing, quantitative data as well as generalization of research findings (Alharahsheh and Pius 2020). However, according to Nickerson (2022), interpretivism is a qualitative research philosophy wherein reality is a social construction based on the experiences and interactions of individuals. It aims to comprehend the meanings, assumptions, and judgments of the scholars adopting its approach. Also referred to as constructivism, the general features of this research philosophy typically involve subjectivity, contextual understanding, in-depth exploration alongside emergent design (Mbanaso, Abrahams and Okafor 2023). Meanwhile, to narrow the divide between positivism and interpretivism, Dolan, Nowell and McCaffrey (2022) asserted that pragmatic research philosophy combines positivism and interpretivism paradigms according to the study questions



**Figure 3.1:** Holistic research methodology flowchart (Source: Designed by Author)

and aims. This usually entails practicality, mixed methods and problem-focused research attributes as pragmatists hold that the usefulness of the study findings in real-world applications should determine the choice of research methodology (Maarouf 2019).

Overall, it is imperative to choose the right research philosophy since it oftentimes influences the entire research process. The choice is influenced by several variables, such as the research question and objectives, nature of the study problem, availability of resources, researcher's personal convictions and whatnot (Pham 2018). On this wise, this study adopts the pragmatic research paradigm as the concept of energy-efficient green building has immediate applications to the actual world, being valued by practical ramifications. Also, since the study is conducted in South Africa, identification and context-specific application of solutions are its main focus because of its unique environmental setting. Moreover, certain objectives in this study aim to maximize the potential for energy performance and efficiency in buildings, which are concrete problems that requires workable solutions. This premise aligns with the pragmatism-based approach to problem-solving.

### **3.3. Research Approach and Design**

Research approach is the broad viewpoint and methods that usually direct the researcher's investigation, which could be either deductive or inductive (Woiceshyn and Daellenbach 2018). The deductive approach begins with a theory or hypothesis and verifies it via gathering and examination of facts. Conversely, the inductive research includes drawing conclusions or patterns directly from the data. Hence, this study suitably alternates between the premises of both approaches to clarify and come up with answers to the research problem. For instance, the study employs the deductive approach as the aim and objectives are based on existing principles and theories involving climate change, sustainable construction, energy efficiency, and such like. This study hypothesized about how climate change impacts occupants' wellbeing and building performance. Understanding these valuable insights consequently helped in deducing energy-efficient and climate-responsive strategies for buildings (Bamdad *et al.* 2021). On the other hand, the descriptive nature of this study uses inductive approach to interpret the knowledge corpus of the green building subject in a qualitative manner (Darko and Chan 2016).

Mbanaso, Abrahams and Okafor (2023) mentioned that research design simply refers to the general strategy or method used by the researcher to address the study objectives and provide answers to the research questions. Some scholars alluded that it serves as a roadmap for conducting any research endeavour, thus directing the choice of data gathering methods, data processing approaches, and findings interpretation (Asenahabi 2019; Sileyew 2019). Typical research designs could be either experimental, surveys, case studies, ethnography or mixed

approaches, while the chosen strategy is mainly determined by the research problem, available resources and whatnot (Mbanaso, Abrahams and Okafor 2023). According to Turale (2020), the overarching plan for carrying out a particular study is usually determined by the research strategy. Generally, the main strategies to research can be either qualitative or quantitative. The qualitative strategy is ideal for investigating intricate occurrences, comprehending experiences, and creating detailed descriptions by using methods like interviews, observations, and textual analysis to gather non-numerical data (Turale 2020). On the other hand, the quantitative strategic approach entails gathering of numerical data and the application of statistical or parametric analytic techniques (Trivedi and Chan 2023). It is suitable for finding out how variables are related or connected, gauging trends, and drawing broad conclusions.

This study specifically employed the mixed-method research design alongside both qualitative and quantitative strategies. This is because monitoring energy usage pattern and savings for instance, requires a quantitative approach to help in analysing numerical data. Meanwhile, the qualitative methods were used to learn more about scholars' perspectives and experiences with green building concept and practice (Debrah, Chan and Darko 2022b). Moreover, the selection of detailed case studies of climate zones and reference buildings in this study normally entail a qualitative approach to analyse their performance data. This helps to proffer various strategic solutions from the results.

### **3.4. Research Method and Sampling Technique**

According to Al-Ababneh (2020), the phrases "research methodology" and "research method" are frequently used synonymously in academic research although they pertain to different components of the research process. The former entails the entire action plan that directs the overall research process by describing the guiding principles and justification for the research design alongside the strategy used to address the study's goals or objectives. Conversely, a research method describes the precise procedures, tools, or instruments that are utilized to gather and examine data in accordance with the specified research methodology (Sileyew 2019). In other words, research method is the theoretical and ideological groundwork laid by research methodology. Based on pragmatic research paradigm, the research methods for each objective of this study are summarized in the parts that follow.

**Objective 1:** *To provide an overview on status-quo of green building development in South Africa with a view to provide roadmap for improvement.*

This objective entails an in-depth overview on applied research and industrial developmental efforts regarding green construction practices. This was followed by a review of the researchers' knowledge and opinions on the subject to help with decision and policymaking. Specifically,

the triple bottom line (TBL) theory serves as the study's guiding theoretical framework. The interaction of the environmental, social, and economic facets of green building is emphasized by the TBL theory (Mushi, Nguluma and Kihila 2022a), while their implications are subjected to South Africa's domain. The study is descriptive in nature and employs inductive deduction to evaluate the knowledge corpus on a qualitative level. In this case, data were collected by a scoping literature review, mapped out and summarized via patterning chart and are analysed through content analysis. Details about the procedures are delineated in Chapter 4.

#### Sampling method:

The purposive and snowball sampling methods were employed for this objective. In specifics, selecting sources or studies that are in line with the research objective necessitates purposeful sampling. The snowball sampling entails starting with limited number of sources and then broadening the research based on citations and references found within those sources (Fahlstedt *et al.* 2022b). This technique is particularly helpful for locating obscure or hidden literature that may be difficult to find using conventional search techniques. Generally, an overview of the research landscape is provided in a scoping review alongside mapping of available literature and major focal point. Given that this objective centres on green building in South Africa, both sampling methods were deemed suitable to provide a balanced breadth and depth that gives a clear picture of the current body of knowledge while highlighting any gaps and possible future roadmaps on the subject. This approach aligns with previous studies in literature about green building subject (Debrah, Chan and Darko 2022b; Fahlstedt *et al.* 2022b).

**Objective 2:** *To examine the energy-saving potential of incorporating building-integrated greenery systems towards climate-resilience in the subtropical climate zone of South Africa.*

This research objective involves a qualitative method by assembling building energy data to investigate how incorporation of nature-based bioclimatic systems in buildings can reduce energy consumption and increase climate resilience. This uses logical deductive analysis to examine the independent parameters relevant to the study. The building geometry and greenery system specifications were used in collating input data while the parametric methods such as heating and cooling design analysis were used for investigating the energy-saving capabilities. The research methods and materials are well elucidated in Chapter 5.

#### Sampling method:

Choosing the right sample strategy is essential because this objective focuses on the maximized energy-saving capacity of building-integrated greenery systems in a subtropical environment. The non-probability purposive sampling method was adopted since it allows the researcher to select structures or buildings with specific energy usage profile and high chance to implement

greenery systems. Promisingly, this method has been duly applied by scholars like Keyvanfar *et al.* (2014) and (Mustaffa and Kudus 2022) who alluded that although this method might not be statistically typical of the full population, it might enhance research in this context by offering in-depth insights into exceptional cases of greenery integration and energy efficiency. Considering some constraints such as practicability and generalization, it enables focusing on relevant case buildings that helps in achieving the study's aim.

*Objective 3: To investigate the energy-performance of green building renewable energy utilization systems within South Africa's hot and arid climate zones*

For this objective, the research approach aimed to gather detailed insights into existing BIPV installations, encompassing their performance metrics, energy generation, ecological influences, and maintenance needs. Following well established experimental cases in literature, a simulation testbed, via the Polysun software was utilized to model BIPV system energy performance across the two climatic scenarios. These simulations allowed for virtual modelling of building structures to analyze the impact of design elements, orientations, and system configurations on energy efficiency. Additionally, the research conducted inclusive case studies in the comparable climate zones, enabling a comparative analysis of different BIPV technologies, materials, and installation methods. This comparative approach aimed to ascertain the suitability and best practices for BIPV integration specifically tailored to South Africa's hot and arid climatic conditions.

#### Sampling method:

Regarding the sampling technique, a purposive approach was employed to map out sites and hypothetically model a building within the targeted regions known for existing or planned BIPV installations. These selections were made considering various architectural designs, orientations, and BIPV configurations, ensuring representation across diverse conditions. Stratified sampling strategies further categorized the sample based on different climatic zones, building types, BIPV technologies used, installation ages, and orientations. This method aimed to create homogenous groups for analysis, offering insights into varying scenarios within South Africa's hot and arid regions.

### **3.5. Study Area**

In this research, the study's geographical focus is South Africa. With a population of about 60 million and an urban growth rate nearly 70%, the country is uniquely positioned as Africa's southernmost nation (Agbajor and Mewomo 2024). Having a total land mass of 1213090 km<sup>2</sup>, it ranks as the 9<sup>th</sup> and 25<sup>th</sup> largest nation in Africa and the world respectively with its borders marked by a combination of two large oceans (Manyevere *et al.* 2017). The country consists of nine

provinces that comprise extremely diverse topography and geographical coordinates with the latitude spanning from 22°S to 32°S while the longitude extends from 16°E to 33°E as shown in Figure 3.2.

Being a developing Global South country with promising potential for economic growth, the study area is deemed suitable to conduct research on optimized energy-efficient green building. Positively, the construction industry makes a sizable contribution to the country's GDP as it recorded a value of about 111 billion rands (roughly US\$6.1 billion) in 2021, showing a fair amount of the capital growth and national development (Statista 2022). Moreover, South Africa is recognised as Africa’s first country to embrace the green building concept as well as being the first member nation of the World’s Green Building Council (Mushi, Nguluma and Kihila 2022a). However, climate-responsive green building research advancements has not fully taken off despite the abundance of highly regarded green construction developments around the nation. Taking the impacts of climate change on buildings into consideration, there is need to explore carbon-neutral strategies for existing buildings. This makes an ideal opportunity to examine the integration of strategic ecofriendly energy resource options for buildings in South Africa.

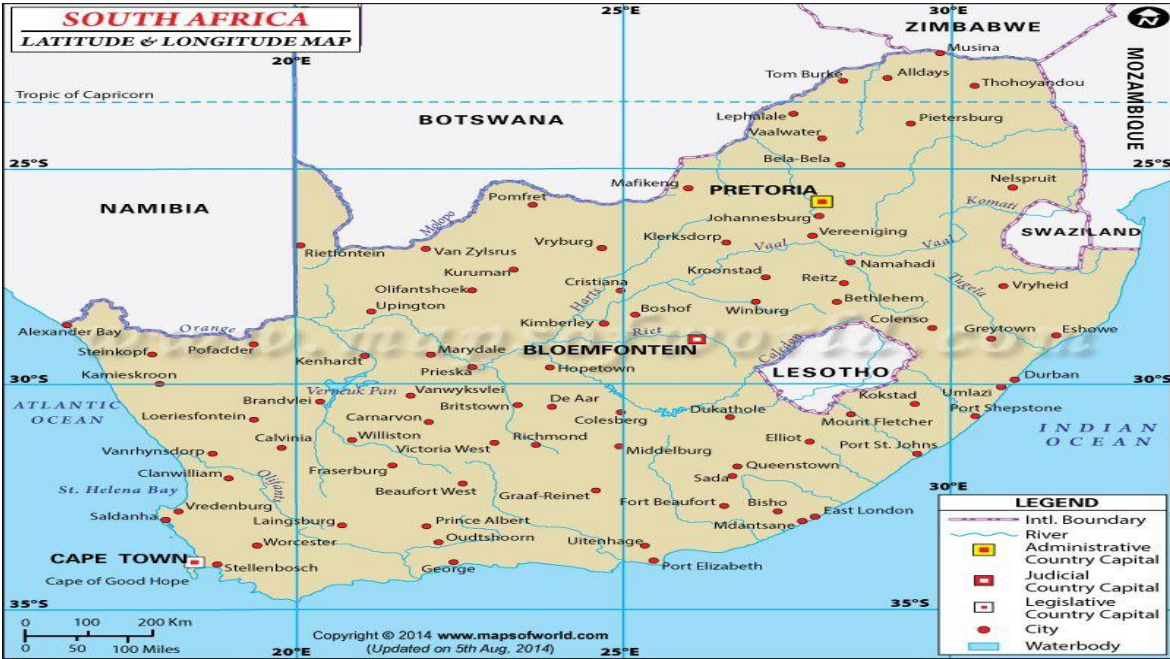


Figure 3.2: Geographical representation of the study area (Mapsoftheworld.com 2023)

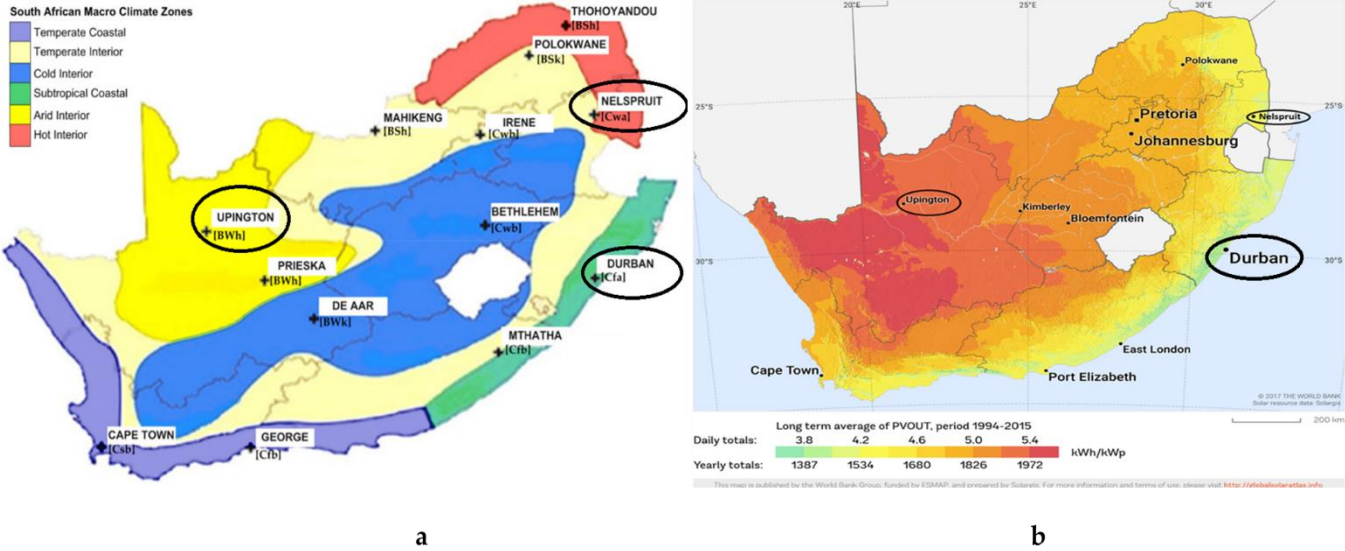
### 3.6. Study Population and Sample Size

Schuller *et al.* (2014) defined population as the entire group of people in a geographical region whose characteristics are to be estimated. More so, Bornstein, Jager and Putnick (2013) defined the term "study population" as the entire collection of variables being observed, which includes all objects or people in any study field. For this research specifically, the first objective sought to investigate the current state of green building development in South African built environment while focusing on sustainable energy and technologies. Thus, the population space encompasses

the entire country as delineated in Chapter 4. It is noteworthy that sample size for this objective is well stated in the Chapter 4 also.

Meanwhile, due to its varied geology and vast landmass, South Africa is marked by a wide range of climatic zones, from arid to temperate and subtropical. The country's climate is substantially influenced by its geographic location. This forms the rationale for selecting the study population for the remaining objectives of this research. Figure 3.3a shows the country's six climatic zones according to South Africa National Standards. These climatic regions have an impact on the nation's weather patterns, vegetation, and general environmental circumstances. Hence, for this research, the target population comprises three out of the six climate regions, namely: subtropical coastal, arid interior and hot interior, extending across four provinces of the country. Usually, climate zones and the thermal conductivity of the building envelope have a direct impact on how much energy a building uses (Himmetoğlu *et al.* 2022). From Figure 3.3, the three target regions were selected as they have the knack for bioclimatic energy-efficient building designs which can help ameliorate carbon neutrality and climate resilience in the built environment.

Meanwhile, the practical impossibility of making the research investigation and inference from the entire population demands the adoption of selecting a handy group of elements. A sample can be referred to as that selected portion or subset of the study population which have been chosen through a sampling process for the purpose of conducting the research investigation. Objectives 2 and 3 of this research considered three specific pilot regions (one from each climate zone). This comprises Durban, Upington and Nelspruit which considerably represent subtropical coastal, arid interior and hot interior zones respectively. Chapters 5 and 6 provided more extensive details about these study locations.



**Figure 3.3:** South Africa map: (a) macro climatic zone and (b) photovoltaic power potential (Mabasa, Lysko and Moloï 2021)

### **3.7. Data Collection Instrument**

This study adheres to the pragmatic research philosophy, which incorporates a variety of research procedures, strategies, and research approaches. It is essential to use the right data collection tools to ensure the collection of correct and pertinent data for each study purpose. Because of this, and to assure better comprehension, the data collecting, and analysis methodologies are identified and detailed individually for every single one of the research objectives in Chapters 4, 5 and 6.

Summarily, the first objective utilized a scoping review to attain a deeper knowledge of the subject of green building. Typically, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses for Scoping Reviews (PRISMA-ScR) flowchart diagram was adopted. It provides a clear and succinct overview of the review process by representing the flow of research through different stages of the meta-analysis visually. (Levac, Colquhoun and O'Brien 2010). In this study, details on how the selection of 228 literal research works, their eligibility, screening, and inclusion of in the final review were made available via this reporting instrument. Upon the final screening, 33 scholarly works relevant to South Africa's domain were utilized for content analysis. These are covered in detail in Chapter 4.

The second objective focused on energy-saving ability of integrating bioclimatic nature-based systems in subtropical climate buildings. Thus, data collection tools include building geometry and greenery system specifications. In this study, a checklist data sheet was designed to record the specifics of the chosen structures' greenery systems. the records of the specified chosen building and greenery systems. This information includes building dimensions, style, building materials, types of vegetation, and covering area. Also, meteorological data were employed as additional research instrument. The study period's climate and its effects on building energy performance were clearly determined using historical weather data for Durban, which included temperature, humidity, solar radiation, and other pertinent climate characteristics. These are fully reported in Chapter 5. The third objective centres on improved photovoltaic systems' energy efficiency in South Africa's hot and arid locations by them integrating into green building. Like Objective #2, weather data was used as the research tool. These were combined with specialist software to aid in trend analysis and visualization, pattern recognition, and energy performance comparison across various BIPV installations. In Chapter 6, they are extensively detailed.

Additionally, for the three objectives, an in-depth survey of literature in order to gain a better understanding of the topic under study served as the secondary source of data gathering. Scopus, Web of Science, and Google Scholar were used as scientific databases to compile a list of scholarly articles pertinent to the goal of this study.

### **3.8. Inclusion and Exclusion Criteria**

To explain the justification for the selection of the study sample, it is critical to clearly define the inclusion and exclusion criteria in any research technique. In this study, the following inclusion criteria were employed for each research objective, namely:

#### Objective #1

- A full account was provided by empirically based research publications.
- The study is conducted within the borders of South Africa.
- Studies within the scope of green building, sustainable construction, or energy-efficient structures are included.

#### Objective #2

- For the research to be relevant to the climate and geographical context, this includes case reference buildings situated in the subtropical coastal climate of Durban.
- This includes structures with the ability to incorporate integrated greenery systems into their retrofitting design, such as green walls, roofs, or interior gardens.
- Considering functional use, institutional building was chosen to evaluate the energy-saving potential of nature-based green systems.
- Before implementing greenery systems, the studied buildings comprised readily available data on their energy usage.

#### Objective #3

- Considering functional use, residential building was chosen to investigate the energy-performance of building integrated photovoltaic (BIPV) systems.

### **3.9. Chapter Summary**

The chapter served to validate the study's methodology, beginning with the foundational philosophy and rationale. It then outlines the research approach, including design, data collection, and analysis techniques, ensuring the study's objectives are met.

# CHAPTER 4

## Green building research in South Africa: A scoping review and future roadmaps<sup>2</sup>

### 4.1 Chapter Overview

This chapter provides a scoping analysis of the academic investigation into green building research. The objective is to supplement the dearth of research findings on the country-level synthesis of green building research, with a particular emphasis on South Africa. Firstly, the motivation and incitement are provided in the introductory section. Secondly, an overview on related works on green building from a global spectrum alongside the current state of the construction industry in South Africa is presented in Section 4.3. The research's techniques and materials are shown in detail in Section 4.4. Typically, the preferred reporting items for systematic reviews and meta-analyses for scoping reviews (PRISMA-ScR) framework was employed. Study's findings with explicit discussions are unveiled in Section 4.5 and 4.6 respectively. Therefrom, a summarized conclusion is provided at Section 4.7.

### 4.2 Introduction

It is widely acknowledged that the various anthropogenic activities from different world economic sectors have several potential negative effects on the natural environment. The architecture, engineering, and construction (AEC) sector is no exemption but propels this issue as buildings account for about 40% of the world's final energy expenditure and greenhouse gas (GHGs) emissions apiece, especially in this rapid urbanization era (Zuo and Zhao 2014; Aghimien *et al.* 2021; Deepak, Vijay K and Arvinder 2022). The dire consequences emanating from climate change have generated global concerns and concerted efforts that are channelled towards a resilient and sustainable AEC industry (Debrah, Chan and Darko 2022a). Part of these unified efforts is the evolution of the green building (GB) concept which emerged as a result of the “*energy crisis*” and “*green revolution*” in the ‘70s and ‘80s respectively (Wuni, Shen and Osei-Kyei 2019). While diverse definitions abound for GB, it can be simply defined as “such a one that is capable of decreasing or eliminating negative impacts on our climate and natural environment and can create positive impacts throughout its entire lifecycle” (World Green Building Council). In other words, GB seeks to address the interplay between people, architecture, and the environment, while preserving the latter from destruction as a result of activities

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<sup>2</sup> This chapter is largely based upon the published paper:

F.D. Agbajor & M.C. Mewomo (2022). “Green building research in South Africa: A scoping review and future roadmaps.” *Energy and Built Environment*, (2022), <https://doi.org/10.1016/j.enbenv.2022.11.001>

from humans and the built environment (Li *et al.* 2020).

GB, being a promising panacea to resource depletion; urban heat island; biodiversity extinction; climate change, and whatnot, has sparked public interest and gained momentum globally in past decades (Wuni, Shen and Osei-Kyei 2019). This is evident through cardinal universal campaigns (e.g. the Paris Agreement), formation of national and global networks (e.g. World Green Building Council), enactment of policies and rating systems (e.g. LEED, BREEAM, Green Star, etc.), construction of iconic and reference infrastructures (e.g. Shanghai Tower, China), among others (World Green Building Council ; Zhang *et al.* 2016; Shan and Hwang 2018a; United Nations Climate Change 2022). Consequently, myriads of empirical, exploratory, and analytical studies have been fruitfully conducted by the research community to unveil the recursive trends, status, and prospects of the GB subject. For instance, Wu, Peng and Lin (2017) presented a comparative evaluation of a lifecycle carbon assessment on GBs and non-GBs via a building environmental load evaluation system database, and discovered that the whole lifecycle CO<sub>2</sub> emissions is significantly higher in non-GBs. The study of Lu *et al.* (2018) employed both quantitative and qualitative data to ascertain the profound impact of GB technology in minimizing construction waste during demolitions. Cohen, Pearlmutter and Schwartz (2019) applied the game theory technique to assess the issues surrounding GB promotion in Israel. Atanda and Olukoya (2019) provided a roadmap toward the formation and adoption of GB standards in Nigeria with reference to the Leadership in Energy and Environmental Design (LEED). Wen *et al.* (2020) explored the significance and impact of GB on sustainable development goals (SDGs) via an analytic hierarchy process-based mapping tool, while Elnaklah, Walker and Natarajan (2021) investigated occupants-related impacts of transiting from conventional buildings to GB. Besides the aforesaid studies, several scholars have provided informative reviews on specific themes and the broad scope of GB research using different techniques such as critical review/content analysis (Mattoni *et al.* 2018; Mushi, Nguluma and Kihila 2022b), scoping/systematic approach (Akomea-Frimpong *et al.* 2022; Debrah, Chan and Darko 2022b), bibliometric/scientometric analysis (Darko *et al.* 2019; Wuni, Shen and Osei-Kyei 2019; Det Udomsap and Hallinger 2020; Li *et al.* 2021b; Oguntona, Aigbavboa and Thwala 2021), text-mining approach (Wu *et al.* 2021), and so on.

By and large, the array of previous reviews has offered holistic and invaluable insights, thus serving as helpful references in exploring new research directions alongside facilitating decision-making by governments and practitioners in the AEC industry. Nonetheless, some apparent limitations exist among them as most of these studies were generally veered towards a global lens (Wuni, Shen and Osei-Kyei 2019; Wu *et al.* 2021) and continental viewpoint (Oguntona, Aigbavboa and Thwala 2021; Mushi, Nguluma and Kihila 2022b), which may generate some bias arising from the neglect to consider the variance of GB research from a national outlook. While the global south lags in GB studies when compared to developed climes, few countries are thriving (Li *et al.* 2021b), and this study seeks to fill

gap. Investigating what has been done specifically in a certain city-state is needful to promote an all-inclusive GB research from a countrywide standpoint in other localities. In this light, the current work is aimed at exploring the emergence and synthesizing the existing knowledge of GB research in South Africa through a scoping literature review.

### **4.3 Related works**

#### ***4.3.1. Overview of reviews in GB research***

The duo of *energy* and *carbon* are fundamental themes that have spurred global movement towards environmental protection. Optimization of the former's efficiency while decoupling the emission of the latter from AEC's related activities is the sector's keen goal, resulting in several innovations, policies, and events (Elnaklah, Walker and Natarajan 2021; Li *et al.* 2021b; Akomea-Frimpong *et al.* 2022). GB, being an ideal measure to achieve this, may be defined as an integrated methods, approaches, and construction products that enhance resource conservation with little or no ecological pollution than traditional buildings (Zuo and Zhao 2014; Akomea-Frimpong *et al.* 2022). An all-inclusive analysis of literature revealed the numerous empirical and scholarly reviews were undertaken within the GB spectrum with the prime goal of having a wider picture. Over the years, several themes have emerged across the field of GB, the major ones focusing on its benefits, drivers, barriers, promotion strategies, GB standards and certification systems, project delivery, occupants related issues, financing schemes, and many others. For instance, Olubunmi, Xia and Skitmore (2016) provided a systematic study on GB incentives and affirmed the need for governments to revamp their GB incentive strategies while Lu *et al.* (2020) gave an overview relating to carbon emissions of GB projects via data mining. Table 4.1 gives an overview of selected GB reviews distributed within the core themes. For more reviews on GB, readers can consult refs (Mattoni *et al.* 2018; Det Udomsap and Hallinger 2020; Li *et al.* 2020; Li *et al.* 2021b; Wu *et al.* 2021; Joyram, Govindan and Nunkoo 2022).

#### ***4.3.2 Overview of AEC sector and GB in South Africa***

South Africa, being Africa's country furthest to the south, is bordered by a mix of two major oceans alongside adjoining countries and is considered as the world's 25th largest country by land mass with a population around 59.4 million and urban growth rate of about 67.4%. Consequently, the building and real estate sector contributes substantially to the nation's gross domestic product (GDP) and provides a reasonable quota of the country's capital formation. Meanwhile, this sector of economy is energy-dependent as most South African buildings (mainly commercial, industrial and institutional buildings) are energy-driven and residential buildings, for instance, are responsible for 1/5 of overall energy use in the country (Oguntona *et al.* 2019b). In the meanwhile, as predicted by the United

Nations, 90 percent of urban growth is forecasted to happen in Asia and Africa in the next 30 years (Nations" 2015), which makes the subject of GB or sustainable construction of utmost importance.

With respect to GB matters, the region is Africa's first nation to be a member of the World's GBC. Noteworthy, the Green Building Council of South Africa (GBCSA) was established in 2007 and therefrom sets the pace for implementing locally made GB rating tool for the rest of Africa (Crafford, Blumentritt and Wessels 2017b). Additionally, several building projects (> 600) have been acclaimed to have the label of this rating tool while huge investment is being disbursed to the council yearly to heighten GB implementation.

Despite the boatload of the acclaimed GB development within the country, scientific research breakthroughs have not fully thrived. Besides, a holistic review that elucidate the extent of research within the federation has not been presented to the best of our knowledge. Thus, this study aims to tackle this unexplored terrain of the subject matter via a scoping review approach.

**Table 4.1:** The major inputs of extant GB reviews across diverse GB topics

Ref	Region/ Domain	Major contributions to green building	Focused aspects of review						Review approach	Year	
			Finance	Regulations & Rating Systems	Energy & Environment	Project Delivery	Design & Materials	Digital Technologies			
(Li <i>et al.</i> 2022)	Global	Provided visualized evaluation of GB studies in the context of relevant stakeholders.				✓			Bibliometric	2022	
(Joyram, Govindan and Nunkoo 2022)	Global	Analysed the factors impacting occupants' choices to adopt eco-block GB technology.						✓	Systematic	2022	
(Ikudayisi <i>et al.</i> 2022)	Global	Developed a conceptual outline for integrated design process and GB project delivery.		✓		✓		✓	Critical review	2022	
(Debrah, Chan and Darko 2022a)	Global	Broadly reviewed the application of artificial intelligence (AI) techniques in GB.							✓	Scientometric and systematic	2022
(Chen <i>et al.</i> 2022a)	Global	Examined the critical success factors (CSFs) and their significance in promoting GB.				✓				Systematic and meta-analysis	2022
(Debrah, Chan and Darko 2022b)	Global	Provided an exploratory study on the role and nexus of green finance in GB projects.	✓							Scoping review	2022
(Cao <i>et al.</i> 2022)	Global	Analysed the progress, problems and outlook of GB absorption and shielding materials.						✓		Critical review	2022
(Woo <i>et al.</i> 2021)	Global	Examined hi-tech blockchain use to building energy performance and carbon credit.			✓				✓	Critical analysis	2021
(Purumal <i>et al.</i> 2021)	Global	Reviewed the fusion of green upkeep ethics to GB maintenance performance indicators.						✓		Critical analysis	2021
(Zepeda-Gil and Natarajan 2020)	Latin America	Analytical survey on the policy advancements towards GB regulations in Latin America.		✓	✓					Critical review	2020
(Wei <i>et al.</i> 2020)	Global	Thoroughly investigated the GB rating systems (GBRS) for evaluating IEQ indicators.		✓	✓					Critical analysis	2020
(Gan <i>et al.</i> 2020a)	Global	An overview on simulation and optimization methods for lifecycle carbon-neutral GB.			✓					Systematic	2020
(Afroz, Burak Gunay and O'Brien 2020)	Global	Examined related case studies on post-certification performance towards GBRS efficacy		✓						Critical analysis	2020
(Zhang <i>et al.</i> 2019a)	Global	Analytical assessment of renewable energy evaluation methods applied to GBRS.		✓	✓					Critical analysis	2019
(Xiao <i>et al.</i> 2019)	Global	Provided an all-inclusive review on GB economic areas.	✓							Scientometric	2019
(Mehmood <i>et al.</i> 2019)	Global	Presented an in-depth overview of applied AI and big data for sustainable buildings.							✓	Critical analysis	2019
(Li <i>et al.</i> 2019b)	Global	Investigation on CSFs in GB projects and the major stakeholders involved.				✓				Systematic	2019
(Jami, Karade and Singh 2019)	Global	Reviewed the features, potentials, and applications of hemp concrete in GB projects.						✓		Systematic	2019
(Geng <i>et al.</i> 2019)	Global	An evaluation of post-occupancy-related issues of GB during their operational phase.		✓	✓					Bibliometric	2019
(Ansah <i>et al.</i> 2019)	Global	Holistic critical survey on applied BIM embedded in GBRS.		✓	✓				✓	Critical analysis	2019
(Zhang, Wu and Liu 2018)	Global	A broad overview on the economic viability of GB from a lifecycle viewpoint.	✓			✓				Critical review	2018
(Vishwakarma and Ramachandran 2018)	Global	A prescient review on potent prospects of using green concrete for new GB projects.						✓		Critical review	2018
(Shan and Hwang 2018b)	Global	A comprehensive analysis of the international GBRS.		✓	✓					Critical analysis	2018
(Alwisy, BuHamdan and Gül 2018)	Global	Evaluated the GBRS to determine GB design factors based on criteria ranking.		✓	✓	✓				Systematic analysis	2018
(Esfandiari, Zaid and Azzam Ismail 2017)	Global	A post-occupancy-based evaluation of IEQ metrics in buildings.			✓	✓				Critical review	2017
(Chan <i>et al.</i> 2017)	Global	Examined the diverse barriers inhibiting GB adoption.				✓				Desktop study and qualitative analysis	2017

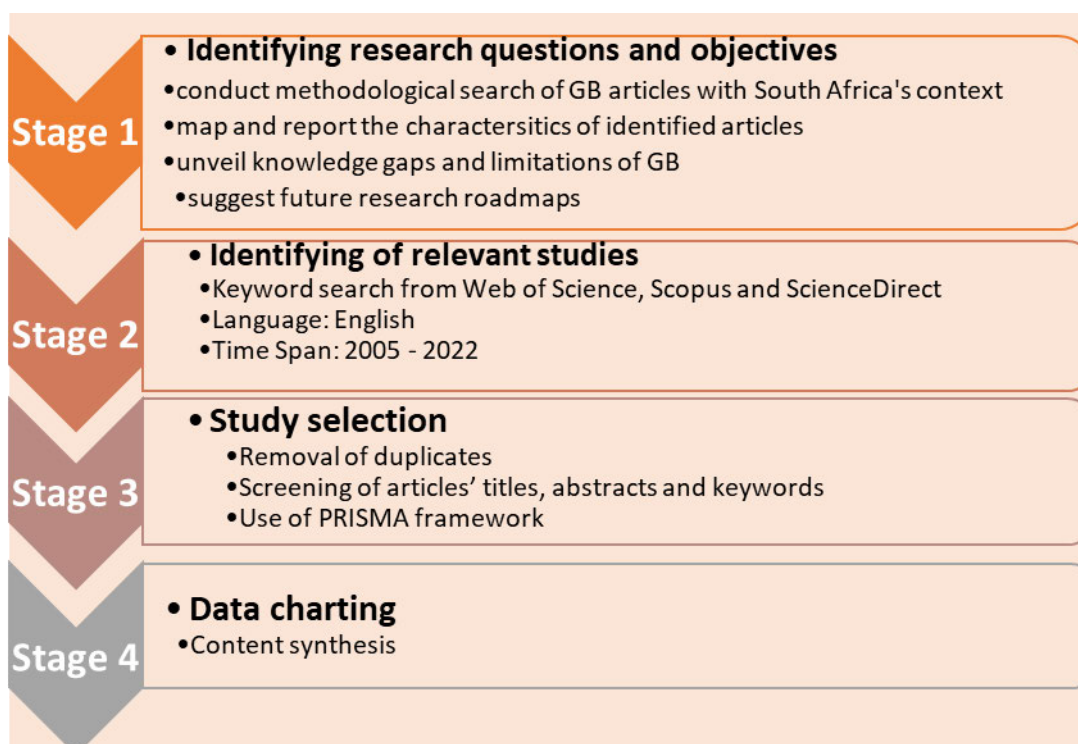
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<i>This review</i>	<i>South Africa</i>	<i>A comprehensive picture of GB research and development to improve decision and policymaking</i>	✓	✓	✓	✓	✓	✓	<i>Scoping review</i>	<i>2022</i>
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## 4.4 Methodology

This study presents a scoping review in order to garner a better erudition of the trend, trajectory and status of GB research in South Africa's AEC industry. Generally, a scoping review is an adequate approach for evaluating the spectrum or extent of a literature body within a specific theme (Peters *et al.* 2020). As a helpful herald to systematic review, a scoping review possesses exploratory or descriptive features with the intention of finding and mapping evident forms of obtainable literature, dealing with holistic review questions, expounding vital concepts, and determining knowledge gaps in a research area (Munn *et al.* 2018; Peters *et al.* 2020). This method has been employed by extant studies in construction engineering and management (CEM) domain (Debrah, Chan and Darko 2022b; Fahlstedt *et al.* 2022a), thus making it an ideal technique to address earlier questions raised in this study. To enable the methodology procedure, this paper considered the approach presented by Levac, Colquhoun and O'Brien (2010) – an advancement to the five-stage outline developed earlier by Arksey and O'Malley (2005) which include (1) *identifying research question*, (2) *identifying relevant studies*, (3) *study selection*, (4) *data charting* and (5) *collating, summarizing and reporting results*. It is noteworthy that stage 5 is fully demystified in Sections 4 and 5, hence, it is not discussed in this current section. In other words, this section considers only *stages 1-4* of the framework provided in ref (Arksey and O'Malley 2005) Moreover, we adopted the Preferred Reporting Items for Systematic Reviews and Meta-Analyses for Scoping Reviews (PRISMA-ScR) framework presented by Peters *et al.* (2015). The research method is presented below as shown in Figure 4.1.



**Figure 4.1:** Study's methodology

#### **4.4.1. Stage 1 - Identifying research questions**

This sub-section ponders on the issues surrounding the aim of this study as clearly defined in Section 1. Following the guide stated in the PRISMA-ScR checklist for objectives of scoping reviews (Tricco *et al.* 2018), our study employed the *Context, Intervention, Mechanism and Outcome* (CIMO-logic) approach (Denyer, Tranfield and van Aken 2008) to frame the review questions. The main questions underlying this scoping review are: (1) What research (**M**) has been conducted towards the development of GB (**I**) projects in South Africa? (2) What are the research gaps and outlook (**O**) of GB research in South Africa's AEC sector (**C**)? The set goals to address these questions are to:

- i. carry out a methodical search of published articles for empirical studies that apply to GB in South Africa.
- ii. map and report the characteristics alongside methodologies employed in the identified studies.
- iii. unveil the knowledge gaps and limitations of GB research domain within the region.
- iv. recommend future trajectories for applied research that can aid GB development in South Africa.

#### **4.4.2. Stage 2 - Identifying relevant studies**

After establishing the research questions, objectives and scope of the study, this section entails finding extant pertinent studies alongside building a choice strategy for search location, search keyword/phrase, search sources/database, selected language and timespan. All these are vital in determining the knowledge corpus wherein the empirical findings and results of those studies are hinged. In a meticulous manner, our study retrieved data from three prominent academic search engines comprising Web of Science Core Collection (WoSC) Scopus (SC) and ScienceDirect (SD) which are consulted based on comprehensiveness (WoSC), wider coverage (SC) and reputable content of original research (SD) (Wuni, Shen and Osei-Kyei 2019; Wu *et al.* 2021). The search was carried out by imputing the search strings while focusing on the relevance and context (for instance, the 9 provinces and major cities in South Africa) of the subject matter. This was achieved by utilizing the Boolean operators "OR" and "AND" combined with earlier-defined well-known terms on GB research (Darko *et al.* 2019; Wuni, Shen and Osei-Kyei 2019) to boost data accuracy and dependability (Debrah, Chan and Darko 2022a) as succinctly illustrated in Table 4.2. A fuzzy search, denoted by an asterisk (\*), was utilized in WoSC and SC databases to provide broader literatures within the study's scope. In the meantime, the study was restricted to studies between 1995 and 2022, in English language, as well as academic articles (research, review and conference papers) from peer-reviewed journals as they provide authoritative and qualitative findings about research conducted. The overall process resulted in a collection of 264 articles after searching and filtering from the three databases and forthwith exported, using the RIS format, to the EndNote software for proper reference

management.

### 4.4.3. Stage 3 – Study selection

The third stage of the methodology involved the screening of the articles’ titles, abstracts, and keywords to enable the detection of works that adhere to the criteria of eligibility. In the first place, we screened the articles from the selected databases automatically via the EndNote tool alongside a back-and-forth manual method to ensure wholesome removal of duplicates. Based on our subjectivity, we adopted a skimming, scanning and double-checking approach on the identified studies’ titles, abstracts, and keywords in order to have a succinct grasp of their content. Moreover, studies that are beyond, or irrelevant to the scope and objectives this paper were exempted via the exclusion criteria, and straightway, we obtained the full texts of eligible articles. Figure 4.2 shows the gradual process of the PRISMA framework for screening and eligibility consideration of the retrieved records, reducing the overall process substantially to 33 articles which were later considered for content analysis. The choice to limit the study to South Africa’s jurisdiction only may account for the minute sample size. Besides, it can also be ascribed to the budding stage of GB research in South Africa, having fewer studies in comparison to some world’s developed regions. Nonetheless, the sample size is reckoned to be satisfactory vis-à-vis some earlier AEC-related studies with fewer sample sizes (Lee, Shin and Park 2022) as well as the 15-study average standard limit for systematic/scoping reviews suggested by (Gray 2020).

**Table 4.2:** Search engines, keywords and results

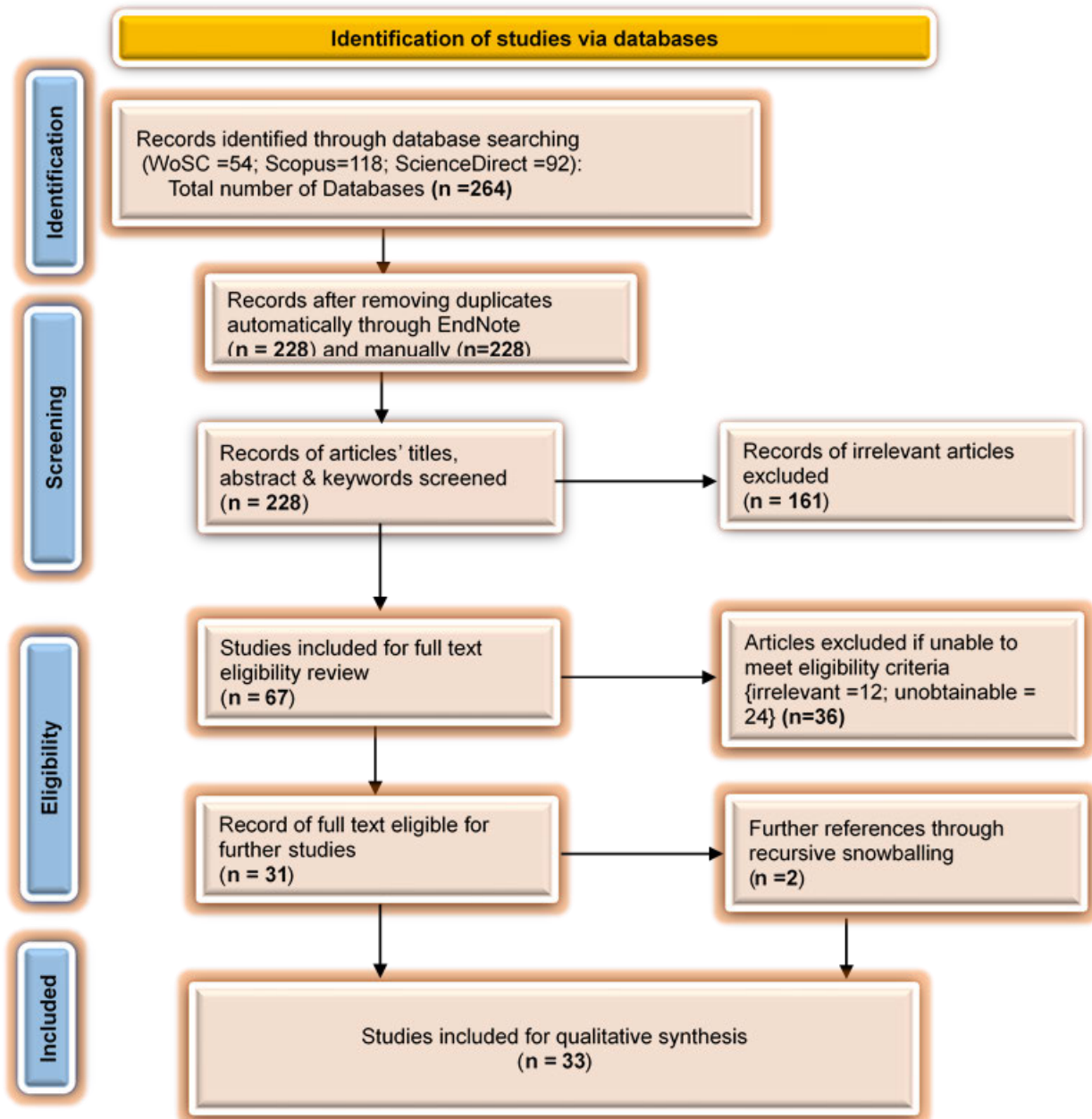
Search Engine	Search String	Query link	Results*
WoSC	("green build*" OR "sustainable build*" OR "sustainable construct*" OR "sustainable hous*" OR "green home*" OR "sustainable home*" OR "eco-friendly build*" OR "eco-friendly home*") AND ("South Africa" OR "Eastern Cape" OR "Western Cape" OR "Northern Cape" OR "Limpopo" OR "North West" OR "Mpumalanga" OR "Cape Town" OR "Soweto" OR "Pretoria" OR "Johannesburg" OR "KwaZulu-Natal" OR "Durban" OR "Guateng" OR "Bloemfontein" OR "Kimberley" OR "East London" OR "Port Elizabeth" OR "Free State")	<a href="#">WoSC QueryLink</a>	54
SC	Same as WoSC	<a href="#">SC QueryLink</a>	118
SD	("green building" OR "sustainable building" OR "sustainable construction" OR " OR "sustainable housing" OR "green home" OR "sustainable homes" OR "eco-friendly building") AND ("South Africa")	<a href="#">SD Query Link</a>	92

\* Results gotten as at the review period, thus subject to subsequent increase in future.

### 4.4.4. Data charting

The retrieved articles, mainly, the one for content analysis, were exported to Excel Sheet. Prior, to this, we decided the kind of details needed. These comprise Authors, Province (where article was mainly authored), the scope of study, study focus, the core results/findings and main research

recommendations. Meanwhile, to facilitate the reporting process, a patterning chart was developed) in order to know the major areas/themes where GB has trod in the last two decades.



**Figure 4.2:** The PRISMA-ScR framework for the study selection procedure

#### 4.5 Findings

This section forms part of the last stage (i.e., *collating, summarizing, and reporting results*) of the scoping review process as highlighted in the preceding section. Thus, we present and demystify the findings of the included studies. Firstly, the overall information of the chosen articles is elucidated, the second part expounds the research approach employed by authors of these studies while we describe the major third parties and sectors involved in GB research in the last sub-section.

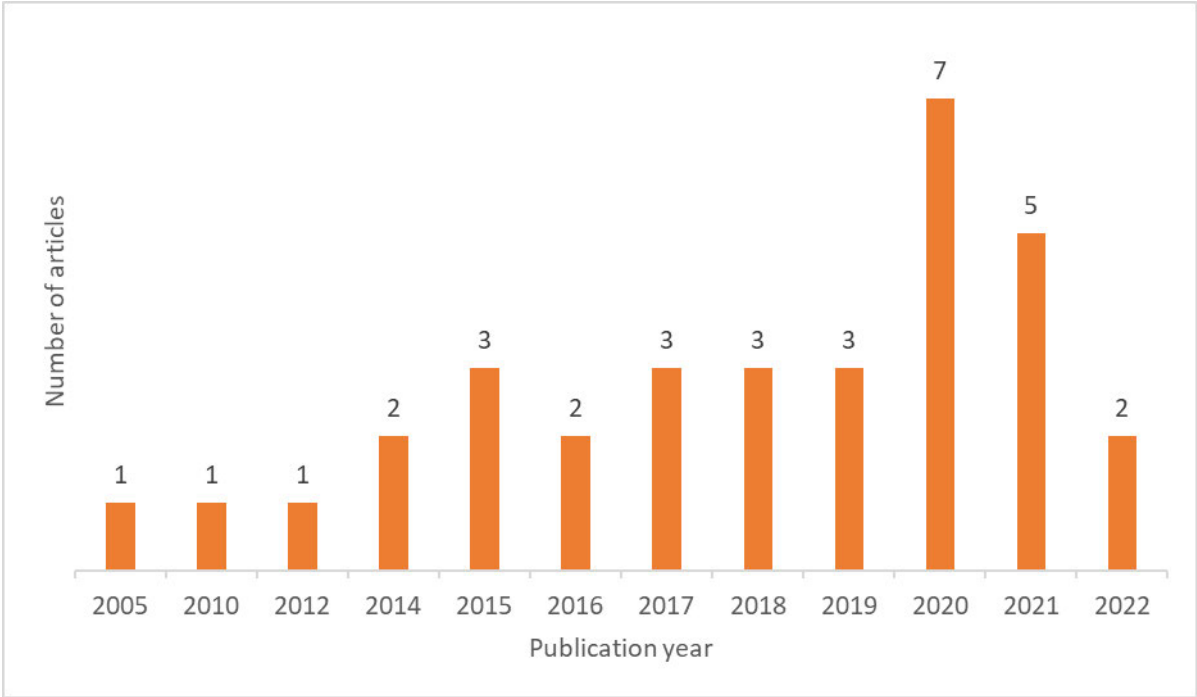
#### 4.5.1 General characteristics of selected GB studies in South Africa

Regarding bibliographic record of GB research, the selected full-text studies considered for qualitative synthesis spanned between 2005 and 2022, indicating that the research on GB in South Africa have traversed for nearly two decades. While the notion and interest behind GB was said to have surfaced earlier in 1996 (Hill, Bowen and Soboil 1996), it was discovered that the foremost relevant and published study obviously emerged in 2005 with the title “*Key performance indicators for infrastructure sustainability – a comparative study between Hong Kong and South Africa*” in which the author conducted a relative evaluation of selected case studies towards green infrastructure. Figure 4.3 demonstrates the publication trend of GB in South Africa and a clearer look at the picture revealed that only three articles were produced between 2005 and 2012 as there were no studies from 2006 to 2009 and 2011. This implies that the scientific knowledge in GB started slowly despite the establishment of the GBCSA in 2007. Nonetheless, some glimpse of cheer sprouted in 2014 and thereafter as more scientific contributions were recorded to depict a gradual development of the subject. There was research decline in 2016 while the three years following had 2 articles apiece. The year 2020 had a giant leap in the research output with 7 articles, hence topping the poll till date. This could be linked to the continual global emphasis on incorporating sustainable construction throughout the building lifecycle which have been fruitfully responded to via diverse projects. One could have envisaged such rising trend in 2021, conversely to expectation, only 5 papers were published while 2 articles are produced as of June 2022. From figure 3, it could be generally inferred that status quo of GB research from its inception till date in South Africa is quite wavering, inconsistent and its wholesome impact have not been fully welcomed by the academic/research community within the region. Herein lies the need for intensified interest along with more scientific and applied research amongst higher institutions in South Africa.

Figure 4.4 illustrates an overview of the South African provinces where the included articles originated alongside their percentage of involvement. Of the 33 studies considered, only 5 (out of 9) provinces were found to have one or more articles accrued to them, the top three being Western Cape, Gauteng, and KwaZulu-Natal at 44.1%, 38%, and 8.80% of research output respectively. Three articles sprung from Free State (2) and Eastern Cape (1) while none emerged from the remaining provinces namely Northern Cape, North West, Limpopo and Mpumalanga. Evidently, the dominance of the top three provinces is an implication of the huge infrastructural development alongside being the major financial hubs of the country. This, to some extent, might have necessitated research towards green construction projects.

All the studies included for content analysis concentrated on three core research realms viz: (1) adoption and implementation of GB (2) environmental sustainability in GB (3) energy-efficient GB

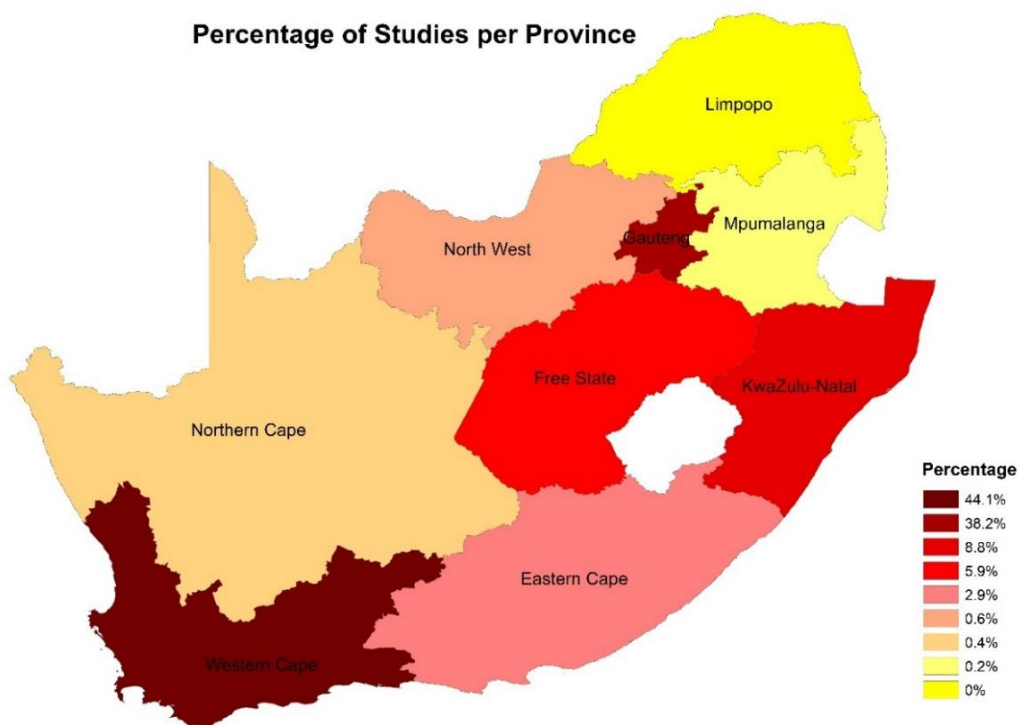
optimization. More than 1/2 of the studies are veered towards issues surrounding the adoption and application of GB in their projects. This proves the essence of this research area considering the holistic effort towards the principal goal of sustainable built environment in the AEC industry. Overall awareness, acceptance, and pragmatic efforts by practitioners in private and public sectors towards GB development plays a crucial role in achieving this aim (Dlamini and Yessoufou 2022). The significance of energy efficiency cannot be overstated in GB as it serves as a driver towards carbon neutrality in the whole lifecycle of building construction. Moreover, the sustainable indoor and outdoor environmental is highly essential in the AEC profession as building users demand comfort and ambience while construction-related activities can impact the natural environment. Figure 5 presents the proportion of these main research domain. In addition, the major sub-themes were found within South African GB studies include *GB adoption and implementation (drivers, benefits, barriers, critical success factors, etc.)*; *GB codes, policies and rating systems*; *Energy performance evaluation*; *Post-occupancy evaluation*; *Sustainability performance evaluation*; *Design, materials and marketing of GB*; and *Stakeholders management and project delivery management*.



**Figure 4.3:** Publication pattern of GB studies in South Africa (2005- June 2022)

From the stance of research outlets, GB studies within the region have been published in 23 distinct journals as shown in Table 4.3. Seven (at 21.2%) of the articles are published in the country’s indigenous journals while the remaining are produced in international counterparts, the prominent ones being *Sustainable Cities and Society*, *Energy and Buildings*, *Building and Environment*, *Journal of Green Building*. ‘*Journal of Engineering, Design and Technology*’ is the most contributing journal accounting for 5 articles (15.2%) to its base. Moreover, three conference papers (representing 9.1%) were reported in journal articles, while four (12.1%) of the included articles had their source in multi-

disciplinary journals, thus reflecting the wide-ranging application of GB across diverse fields globally. However, most (over 50%) of these studies ranked in the 2nd quartile based on Scimajor journal rankings, indicating the paucity of research output in high-impact journals having the best quartile. Future studies within the country can may disburse more focus on emerging and novel research towards more relevant outputs.



**Figure 4.4:** Provinces where published GB related research are originated

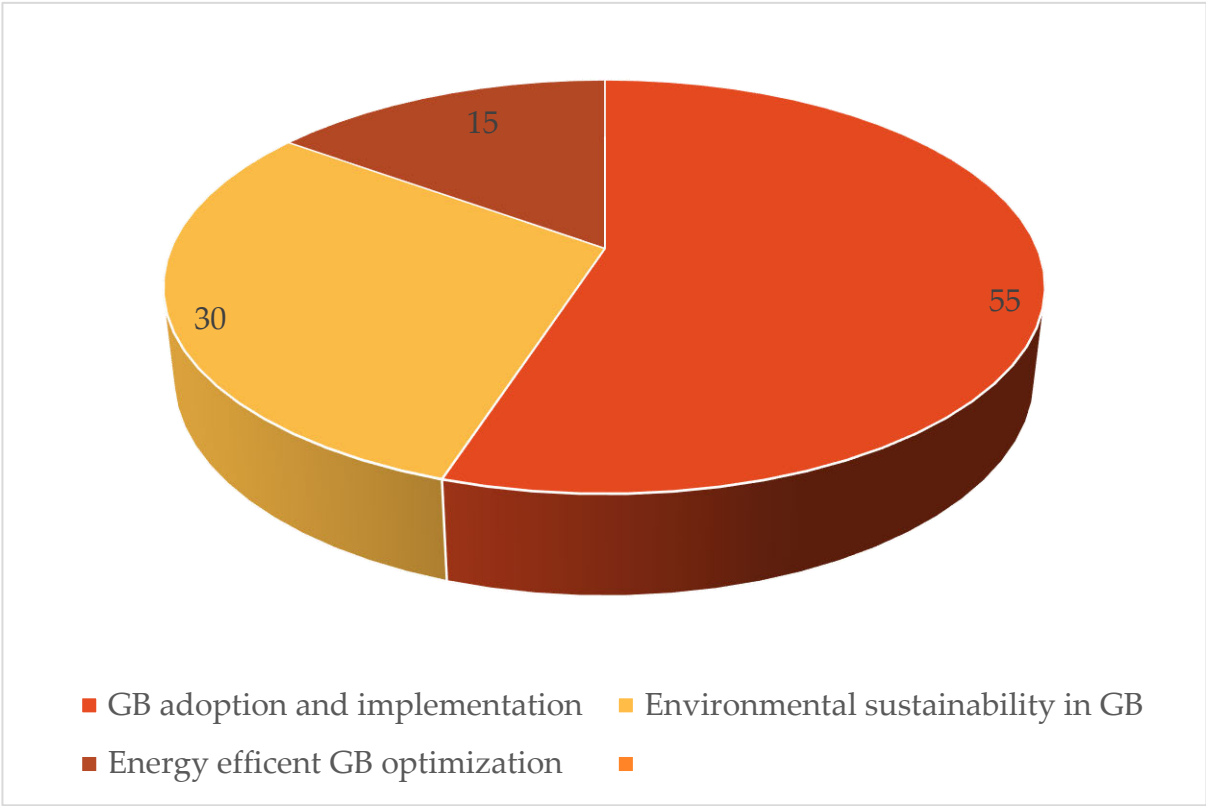
**Table 4.3:** Research outlets of GB studies in South Africa

S/N	Source (Journal name)	No of Documents	Percent (%)	Domain	
				International	South African
1	Journal of Engineering Design and Technology	5	15.2	✓	
2	Sustainability	2	6.1	✓	
3	Urban Forum	2	6.1	✓	
4	Journal of the South African Institution of Civil Engineers	2	6.1		✓
5	South African Journal of Industrial Engineering	2	6.1		✓
6	World Congress on Sustainable Technologies	2	6.1	✓	
7	ACTA STRUCTILIA	2	6.1		✓
8	Smart and Sustainable Built Environment	1	3.0	✓	
9	Sustainable Cities and Society	1	3.0	✓	
10	Energy and Buildings	1	3.0	✓	
11	Building and Environment	1	3.0	✓	
12	Construction Management and Economics	1	3.0	✓	
13	South African Journal of Science	1	3.0		✓
14	International Journal of Housing Markets and Analysis	1	3.0	✓	
15	Journal of Green Building	1	3.0	✓	
16	Advances in Building Energy Research	1	3.0	✓	
17	Business Strategy and the Environment	1	3.0	✓	
18	Journal of Urbanism	1	3.0	✓	
20	Mediterranean Journal of Social Sciences	1	3.0	✓	
21	International Journal of Building Pathology and Adaptation	1	3.0	✓	
22	IOP Conference Series: Earth and Environmental Science	1	3.0	✓	
23	Journal of Physics: Conference Series	1	3.0	✓	

#### ***4.5.2 Methodological characteristics of selected GB studies in South Africa***

In the meantime, most of the articles consider a number of research methods. Over 75% of the 33 articles employed qualitative research approach. In simple terms, these articles considered questionnaire survey as their methodology, about 12% engaged in semi-structured interviews with

professionals in the AEC industry alongside some prominent stakeholders in the built environment such as clients and/or developers. Some authors such as Michael, Zhang and Xia (2017); Fan and Xia (2018) adopted the modelling and simulation optimization using some representative locations as case studies.



**Figure 4.4:** Major themes in South African GB research

**4.6 Discussions**

This section considers the remaining aspect of the PRISMA process’ 5th stage. Therefore, we firstly provide a summarized discourse on the evidence from the included studies via a patterning chart to identify the status-quo of major themes of GB research in South Africa. Thereafter, future research roadmaps were recommended based on the gaps identified while the study’s limitations were highlighted later in this section. Meanwhile an appendix is provided after the concluding remarks to illustrate the analysis of the included studies.

**4.6.1 Synopsis of GB research topics from included studies**

It is evident from this study’s report that GB research is not full-fledged within South African academic/research community despite a plethora of AEC-related higher institutions. Although the country is a trailblazer and at leading-edge of GB studies in sub-Saharan Africa (Mushi, Nguluma and Kihila 2022b), its annual research efforts and outputs are unsteady as highlighted in the preceding section. It is laudable that such provinces as Western and Gauteng are ahead of the curve in promoting

GB research and practice in the academia and industry respectively thereby reflecting its necessity. Nonetheless, research on the subject matter is on a road less travelled among four provinces and herein lies the clamour for empirical and exploratory studies in such localities. In the meantime, such methodological approaches as interviews, questionnaire surveys, mixed methods, literature reviews, comparative analysis and case studies were employed by the 31 included studies. Accompanying these include the methods for data analysis which are statistical (descriptive and inferential), computational, qualitative, and mixed approach.

Moreover, we carried in-depth thematic analysis of the selected studies to discover the dominant themes and some underexplored sub-themes of GB research. An overview is presented in Table 4.4 and Figure 4.5 while succinct discussions are itemized as follows:

#### ***4.6.1.1. Green building adoption and implementation***

Obviously, majority of the studies concentrated on the adoption and implementation of GB. This is deemed necessary as any sustainable construction or GB product is hinged on how the general populace are aware of all-encompassing issues surrounding GB, their willingness to divest non-GB methods and readiness to embrace GB projects. Usually, GB drivers, benefits, challenges, key performance indicators are mainly categorised under this aspect. To advance sustainability in South Africa's built environment, Oguntona *et al.* (2019a) examined the core initiatives (drivers and benefits) influencing green construction practices. Their appraisal identified ecosystem protection, indoor air quality and CO<sub>2</sub> emission reduction, as GB top benefits. Similarly, the topmost drivers comprise increased financing incentives, education, and training, developed market for GB materials and goods. Likewise, the pinpointed drivers align with the work of Windapo (2014). The study of Aghimien, Aigbavboa and Thwala (2019); Marsh, Brent and de Kock (2020) among others, discovered reluctance to change, client preferences, concern of rising investment cost, paucity of building codes, among others, as the core barriers influencing sustainable construction in South Africa. The aforesaid studies made clear emphasis on the role of government in promulgating rules and guidelines that would prepare those involved in the construction business to fully embrace GB as well as financing its development. Also, it was argued that access to education, training, and upskilling for stakeholders should be provided by relevant GB organizations such as GBCSA. While these suggestions are vital, it is vague to know whether/not the access to fund green construction projects are readily available to stakeholders involved in sustainable construction. In this light, the monetary incentives for green infrastructural projects can be explored in future studies. Also, more apparent information on the interplay between GB policies and financing schemes by the government are lacking. Further research can take this into account since building codes and standards, effectively supported via funds and haply, subsidized premiums can boost the implementation of GB.

#### ***4.6.1.2. Environmental sustainability in GB***

Creating sustainable and high-performance human shelters especially in the world's ever-expanding regions is a challenge that draws in the concerned stakeholders. To combat the societal degradation related with rapid urbanization as well as to produce a safe environment, clarion calls have been made to adopt and develop long-lasting inventions that can bolster the sustainability of buildings and allied civil infrastructures in form of standards and certification systems. Regarding this area, the worldwide research community have undertaken myriads of studies regarding GB standards, assessment tools, rating schemes, certification systems, and such like. South Africa have fruitfully taken part in these through its GBCSA membership alongside a few studies. For example Hoffman *et al.* (2020), evaluated the patterns and trends in the credits earned by GB-certified projects, which is a crucial aspect of using the Green Star SA tool. The rating level was discovered to have some positive correlation with frequently used credits and a negative correlation with seldom used credits Windapo and Goulding (2015) investigated GB regulations requirements and practices during the operation stage of construction projects. Moreover, authors in ref (Fan and Xia 2018) proposed an optimization model to assist decision-makers in identifying the optimum mix of retrofit alternatives for buildings to achieve policy compliance in the most affordable manner. In the meantime, the technological difficulties associated with these credit systems have not been identified in extant studies. Moreover, a general assessment of the Green Star SA tool has not been explored in most recent works. It is imperative that the lifecycle assessment and environmental impact assessment and how they affect GB design are considered in future studies.

#### ***4.6.1.3. Energy-efficient green building optimization***

Certainly, energy is a strong mainspring of any national growth and sustainable development. Its access, conversion and deployment are directed to diverse activities and tasks within South Africa's built environment. Previous studies, such as Dlamini and Yessoufou (2022) reported carried out a field survey of energy-saving strategies in GB projects. Likewise, the authors in ref (Eromobor, Das and Emuze 2020) focused their study in determining how different building and indoor environmental factors affected how energy-efficient South African university buildings were. In another development, statistics revealed that South Africa buildings often consume 40% of the country's energy, while having significant capacity to save energy. Authors in (Fan and Xia 2018) presented an optimization model to maximize the payback period, retrofitting expenses, energy and water savings, and LEED rating system. There exists dearth of research on the need to evaluate the interaction between the building and indoor environmental features and overall energy performance. Optimizing building energy use particularly for green retrofits can be a strategic means to lessen GHGs emission, curb the impacts of climate change, balance the mismatch between energy demand and supply and alleviate the loadshedding challenge the country is facing. Newly proposed studies could take this

into account both individually alongside their impact and in whole to ensure energy-efficient construction of sustainable buildings. Moreover, for South African AEC industry, energy efficiency should aim at employing less energy to achieve similar level of technological process in construction projects as well as energy supply in buildings.

#### ***4.6.1.4 Identified GB technologies in South Africa***

Ideal incorporation of GB technologies (GBT) is indispensable to fullbring any envisaged GBs and sustainable cities. Some scholars opined that applied GBT should be location-dependent as such factors as climate, economy, environmental goals and standards vary across world regions (Anzagira *et al.* 2022). In South African context, a section of the identified studies focused on material efficiency. For example, Crafford *et al.* investigated the potentials of localized timber products as eco-friendly materials when utilized as roof truss in GB construction within the region (Crafford, Wessels and Blumentritt 2021). Similarly, Windapo *et al.* (2021) went further by evaluating the sustainable performances of wood technology particularly when used for low-medium housing. Actually, timber and concrete constitute the dominant building materials used in South African construction projects. Indeed, material efficiency is important in this current era as they constitute the core elements in the final GB product while efficient and eco-friendly materials are highly essential to reduce anthropogenic impacts created during material production and use. Notwithstanding, such emerging innovative GB materials as eco-blocks, geo-polymer concrete, bio-based phase change construction materials are still unexplored in the country. Besides, further GBT that covers such aspects as energy efficiency, water efficiency, improved indoor climate, GB systems control sparsely presented in the literature within the region. Simply put, GBT refers to the mechanisms deployed in the design, construction and operation phases of buildings to achieve improved sustainable performance. It is imperative to weigh and pragmatically unveil these untapped technologies while considering their lifecycle environmental benefits to future-proof sustainable built environment in South Africa.

**Table 4.4:** Patterning chart of key themes and sub-themes in selected GB studies within South Africa

S/N	Author(s)	Study detail (s)	Research foci within GB sub-themes									
			DR	BE	BR	CSF	CPRS	EPE	POE	SPE	DMM	SPDM
1	Mistry and Spocter (2022)	Investigated eco-estates' use of waste, water, and energy minimization techniques.							✓		✓	
2	Dlamini and Yessoufou (2022)	Assessed the sustainability strategies used in a GB from residents and professionals	✓	✓	✓						✓	
3	Windapo <i>et al.</i> (2021)	Developed a rating tool to assess the sustainability performance of low-income houses									✓	✓
4	Sinxadi and Awuzie (2021)	Measured the lookout of economic sustainability input to effective project management			✓							✓
5	Owoha <i>et al.</i> (2021)	Examined and categorized the GB concepts and accompanying features.							✓	✓		✓
6	Marsh, Brent and de Kock (2021)	Identified stakeholders' perceptions and attitudes on sustainable construction (SC).	✓	✓	✓						✓	
7	Crafford, Wessels and Blumentritt (2021)	Analysed GBRS and lifecycle evaluation methods with an emphasis on wood constructions.						✓			✓	✓
8	Watkins and Sunjka (2020)	Examined the linkages between lean construction and GB all over project's phases.		✓							✓	✓
9	Simpheh <i>et al.</i> (2020)	Identified and grouped the challenges affecting GB adoption in South Africa.			✓							
10	Simpheh and Smallwood (2020)	An integrated model for predicting the probability of adopting SC.	✓	✓	✓							✓
11	Marsh, Brent and de Kock (2020)	Reviewed the drivers of and barriers to the use of sustainable building practices.	✓		✓							
12	Hoffman <i>et al.</i> (2020)	Surveyed the patterns in the credits earned by GB-certified projects.	✓					✓			✓	
13	Eromobor, Das and Emuze (2020)	Considered new policy & practice implications for building retrofits in universities							✓	✓	✓	
14	Boshoff and Mey (2020)	Evaluated the strengths of building energy tools to reduce CO <sub>2</sub> emissions.						✓	✓		✓	
15	Oguntona <i>et al.</i> (2019a)	Assessed the drivers and benefits for encouraging the execution of GB initiatives.	✓	✓								
16	Aigbavboa and Thwala (2019)	Evaluated the IEQ components and their impact on building users.						✓	✓	✓	✓	
17	Aghimien, Aigbavboa and Thwala (2019)	Examined the difficulties with sustainable construction in developing nations			✓							✓
18	Ololade and Rametse (2018)	Considered the drivers to deployment of environmental management system to improve SC	✓									✓

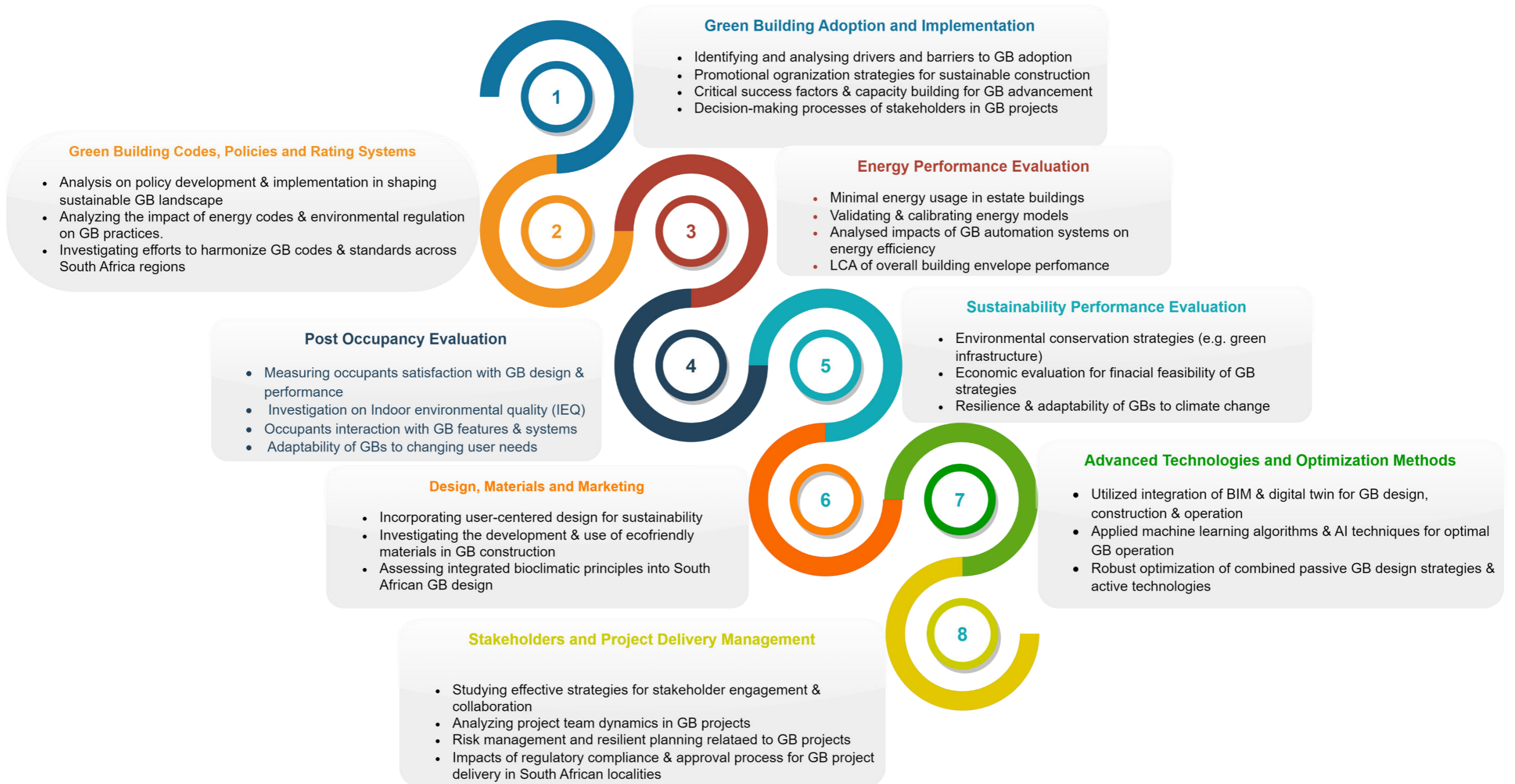
19	Fan and Xia (2018)	Developed an optimization tool to find the best building retrofit pattern and options						✓			✓	✓	
20	Dosumu and Aigbavboa (2018)	Examined the knowledge level regarding light steel for sustainable GB projects.		✓	✓						✓	✓	✓
21	Michael, Zhang and Xia (2017)	Provided an optimal model for a building retrofit with reference to LEED standard.						✓	✓	✓			
22	Ganiyu, Fapohunda and Haldenwang (2017)	Proposed efficient financing solutions towards providing cheap, sustainable housing.						✓			✓		✓
23	Crafford, Blumentritt and Wessels (2017a)	Investigated several roof truss systems in via a life-cycle assessment method.									✓	✓	
24	Sundayi, Tramontin and Loggia (2016)	Examined real estate developers' notion on green development and its fiscal effects.		✓				✓					✓
25	Solanke and Fapohunda (2016)	Analysed the use of e-commerce to enhance materials procurement process in GB growth									✓		✓
26	Windapo and Goulding (2015)	Assessed GB legislation requisites and practices during the project operation stage.						✓			✓		✓
27	Seeliger and Turok (2015)	Examined how developers feel about sustainable urban transformation ideas.											✓
28	Coetzee and Brent (2015)	Considered how property developers and industry professionals perceive the GB costs.							✓		✓		✓
29	Windapo (2014)	Appraised the major GB drivers and their changing tendencies with time.		✓				✓			✓		
30	van der Bank and van der Bank (2014)	Investigated renewable energy policies towards sustainable building development.						✓			✓		
31	Thatcher and Milner (2012)	A comparative analysis of GB on wellbeing of workers.									✓	✓	
32	Ross, Bowen and Lincoln (2010)	Examined how sustainable low-income housing can be attained in emerging economies.							✓				✓
33	Ugwu and Haupt (2005)	A comparative survey of key performance indicators of sustainable infrastructure.									✓		✓
<b>Total of each sub-theme</b>				<b>8</b>	<b>7</b>	<b>9</b>	<b>4</b>	<b>11</b>	<b>6</b>	<b>6</b>	<b>15</b>	<b>7</b>	<b>16</b>

**Note:** **GBAI:** Green Building Adoption and Implementation; **DR:** Drivers; **BE:** Benefits; **BR:** Barriers; **CSF:** Critical Success Factors; **CPRS:** GB Codes, Policies and Rating Systems; **EPE:** Energy Performance Evaluation; **POE:** Post-Occupancy Evaluation; **SPE:** Sustainability Performance Evaluation; **DMM:** Design, Materials and Marketing; **ATOM:** Advanced Technologies and Optimization Methods; **SPDM:** Stakeholders and Project Delivery Management

#### **4.6.1.5. GB standards and policies in South Africa**

Undoubtedly, pragmatically enacted GB standards are proven measures towards climate change mitigation and realization of sustainable built environment. In South African terrain, government regulations play a prominent part in encouraging the adoption of GB and sustainable construction process as duly noted by a few studies (Windapo and Goulding 2015; Hoffman *et al.* 2020). An updated evaluation of these regulations revealed their coverage across national and provincial. The core aims of these standards specifically for GB promotion within the federation is usually delineated while it was discovered that most of these standards veered towards such GB requirements as waste management, material recycling, utilization of eco-friendly materials, pollution prevention, minimal resource (energy, water, materials, etc.) consumption, and such like. For example, a vital part of the National Energy Act of 2008 in relation to GB promotion strives to offer increased generation and utilization of renewable energy resources for the nation's building stock alongside other sectors of the economy, while the Air Quality Act of 2004 and its successive amendments aims at protecting the natural environment by offering reasonable safeguards against pollution and ecological deterioration (*National Environment Management: Air Quality Act 39 of 2004* 2022). Since sustainable construction seeks to cater for the entire lifespan of buildings, some of these legislations endorse guidelines regarding the design, construction, operational and maintenance phases of construction projects and their finished products. A typical case is the City of Cape Town Green Building Guidelines emphasis on design and construction stages based on principles such as local appropriateness, natural environment conservation, among others (*City of Cape Town Green Building Guidelines* 2022). In specifics, both phases deal with such aspects as efficient site planning, passive building design, natural and energy-efficient building materials and methods, and whatnot with requisite recommendations to ensure their implementation. Meanwhile, recent spotlight developments regarding these policies are seen in the launch of the "Green Building Policy" by the Johannesburg City Council (provincial level) and the Public Works Department (national level) (*DPW Green Building Policy* 2022).

In the meantime, pertinent issue surrounding these enacted standards could be linked to the aversion, apathy and slow-paced adherence of AEC sector's project stakeholders within the federation. It is crucial to ensure that construction practices comply with GB legislation requirements as it was pointed out that a few discrepancies exist between actual GB practices and legal standards which may arise owing to conjecture whether these rules are mandatory or voluntary.



**Figure 4.5:** Summarized patterning chart of sub-themes on GB research, development and practice in South Africa

#### **4.6.1.6. GB certification and rating system in South Africa**

GB certification and rating schemes serve as a complementary complement to enacted standards and indispensable enablers to foster GB promotion. Following the launch of GBSA in 2007, South Africa auspiciously made a landmark achievement in establishing a context-based certification and rating system in 2009 (*Green Star Certification 2022*). Since the inception, a building's environmental state can be determined objectively using the Green Star SA rating having some inherent tools that address diverse building typologies as well as different aspects of the building phase (Crafford, Wessels and Blumentritt 2021). Categorically, these tools cover such major environment-based aspects comprising management, indoor environmental quality, energy, transport, water, materials, land use and ecology, emissions and innovation. To attain the threefold parts of sustainability, an additional category was included to cater for socio-economic issues which relate specifically to new buildings. In relation to typical standards employed by some developed world regions, particularly Green Star of Australia, and the United States' LEED rating system, a comparative evaluation indicated that these rating tools have certification procedures to be pragmatically followed by buildings envisaging to be certified. Moreover, these rating systems usually assign weights to newly developed or retrofitting buildings to determine and rank their compliance extent. However, an important subject to be considered in the Green Star SA is the need to further reinforce the standard to fully meet the social and economic requirements of GB.

#### **4.6.1.7. GB incentives and finance mechanisms in South Africa**

Generally, the development of eco-friendly structures typically requires more resources, such as money, than conventional counterparts. Thus, incentives for GB are crucial for advancing green construction practices especially if profound adherence to the promulgated GB policies are envisaged. The federal and provincial governments in South Africa embrace this measure as an avenue to instil the advancement of sustainable construction practice among project owners and practitioners. For instance, the GBCSA provide certain rebates in housing stock and property rates that meet that acquire its rating system (*Incentives to build green in South Africa 2022*). Similarly, the 'income tax allowance' on energy efficiency savings was established by the Department of Energy and the South African National Energy Development Institutes as the implementing agency to safeguard the nation's energy security through energy efficiency methods for buildings and other energy-consuming sectors. By extension, the International Finance Cooperation early in 2022, issued an approximate amount of \$42 million as a loan package to South African non-banking financing company that specializes in offering funding, mentorship, and support services to small and medium enterprises housing projects. This is aimed to amplify the practice of GB as the country keeps seeking solutions to abate climatic menace. Meanwhile, grey areas to be tackled is seen in the demand for net zero and positive energy building retrofit keeps increasing within the region, thereby raising investment prospects which creates some lacuna and the

exigent need to formulate realistic and effective financial models towards the achievement of sustainable buildings.

#### **4.6.2. Future roadmaps and recommendations**

Through a scoping review, our study unravelled the trends and status-quo of GB in South Africa. Without mincing words, some level of advances has been made regarding the subject since its inception via several research approaches, analysis of data and so on. Based on our findings, the following recommendations are solicited both within research and practical standpoints.

##### ***4.6.2.1 Advanced technologies and optimization methods in GB/Data-driven GB optimization methods and technologies***

As the modern world rapidly marches into urbanization, future cities and regions, particularly sub-Saharan Africa will face unprecedented pressures. The significant role of advanced technologies in this current digital era cannot be over-emphasized. GB have been found to offer more benefits during this industrial revolution. Applied research that include such cutting-edge and data-driven digital technologies as internet of things, artificial intelligence, machine learning, building information modelling, blockchain technology, 4D printing and so on, can be embraced in future studies. Promisingly, these tools can be introduced either singly or jointly within each phase of construction projects.

##### ***4.6.2.2. Institutional and regional contribution***

There is an astute need for more GB research to boom throughout the federation. While some provinces have been identified to be at the forefront of research and development, an awakened interest should be extended to unsung regions within the country in order to enhance GB awareness. On this wise, research collaborations are encouraged among higher institutions where GB studies is yet to gain grounds. Moreover, green, and sustainable construction should be introduced to the teaching curricula to transfer such knowledge to students.

##### ***4.6.2.3 Critical success factors in GB***

A consideration of critical success factors (CSFs) is highly essential in promoting GB development. In the meantime, only a few of these were presented from the extant literatures mainly from stakeholders and owners' perspectives. Future research can explore the other categories of these CSFs, particularly, the ones including government, marketing of GB products, management approaches, and so on. Also, the nexus existing these CSFs and how they are incorporated may be put under consideration by future studies.

### **4.6.3 Study's limitations**

While this study employed the scoping review approach to unravel the extent of research carried out, it has its own caveats and limitations. Firstly, all keywords within the GB domain were not explored as it is somewhat impractical to exhaust all the available keywords during the search process. Hence, further studies may decide to include new or more search strings to have newer overview. Unlike systematic reviews, the worth/value of most articles included in the eligibility criteria were not evaluated in this study. Moreover, this study excluded data from other sources such as technical papers, grey literature, among others, and within the confines of only three databases (Web of Science, Scopus and ScienceDirect).

### **4.7 Concluding remarks**

By and large, there have been universal intensified interest in green building while its pragmatic application via numerous projects have witnessed spiral development globally. Several studies have been undertaken to unveil various issues encompassing the theme. In this paper, we provide a literature survey of extant studies on GB within the context of South Africa. The study, being a scoping review, employed the quantitative synthesis approach to unveil previous research trajectories, coin out the major themes, identify the gaps and recommend research roadmaps. The study's findings discovered that GB research is at a gradual developmental stage in the region. More so, the focus of the reviewed studies has been on its adoption and implementation. While this is understandable, this study suggests the need for institutional collaboration in research, applying high-tech digital tools in the lifecycle process of sustainable construction and the need to explore more of the critical success factors, by major stakeholders. Limitations within the study were highlighted. Lastly, in practical terms, this article can serve as a reference for further research and can also be helpful to policymakers, stakeholders, and allied parties and organizations concerned with sustainable built environment in South Africa.

### **4.8 Chapter Summary**

In this chapter, a scoping analysis of academic research on green building was conducted, aiming to address the lack of findings at the country level, specifically focusing on South Africa. The motivation and purpose were established at the outset, afterwards a global perspective on green building research and the current state of South Africa's construction industry. Detailed information about the research methods and materials was outlined, followed by the presentation of the research findings, discussions and salient recommendations for research and practice.

## CHAPTER 5

# Optimized energy-saving potential of building-integrated greenery systems in the subtropical coastal climate of Durban, South Africa

### 5.1. Chapter Overview

This chapter provides a performance evaluation of incorporating nature-based greenery systems into facades of existing buildings. A literature overview on these greenery-based energy-saving systems for green building has been covered in Section 2.6.2 of Chapter 2. Thus, the objective is to investigate how the integration of green walls, green roofs and thermally insulated green envelope materials can provide optimal energy efficiency and mitigation measures over conventional buildings with no green retrofit action under changing climatic situations. Herein, Section 5.2 depicts the methods and materials adopted in conducting the research. Typically, a three-storey university building in the subtropical climate zone of the city of Durban, South Africa was selected as a case study for parametric simulation and analysis. Study's findings with explicit discussions are unveiled in Section 5.3 while a summarized conclusion is provided in Section 5.4.

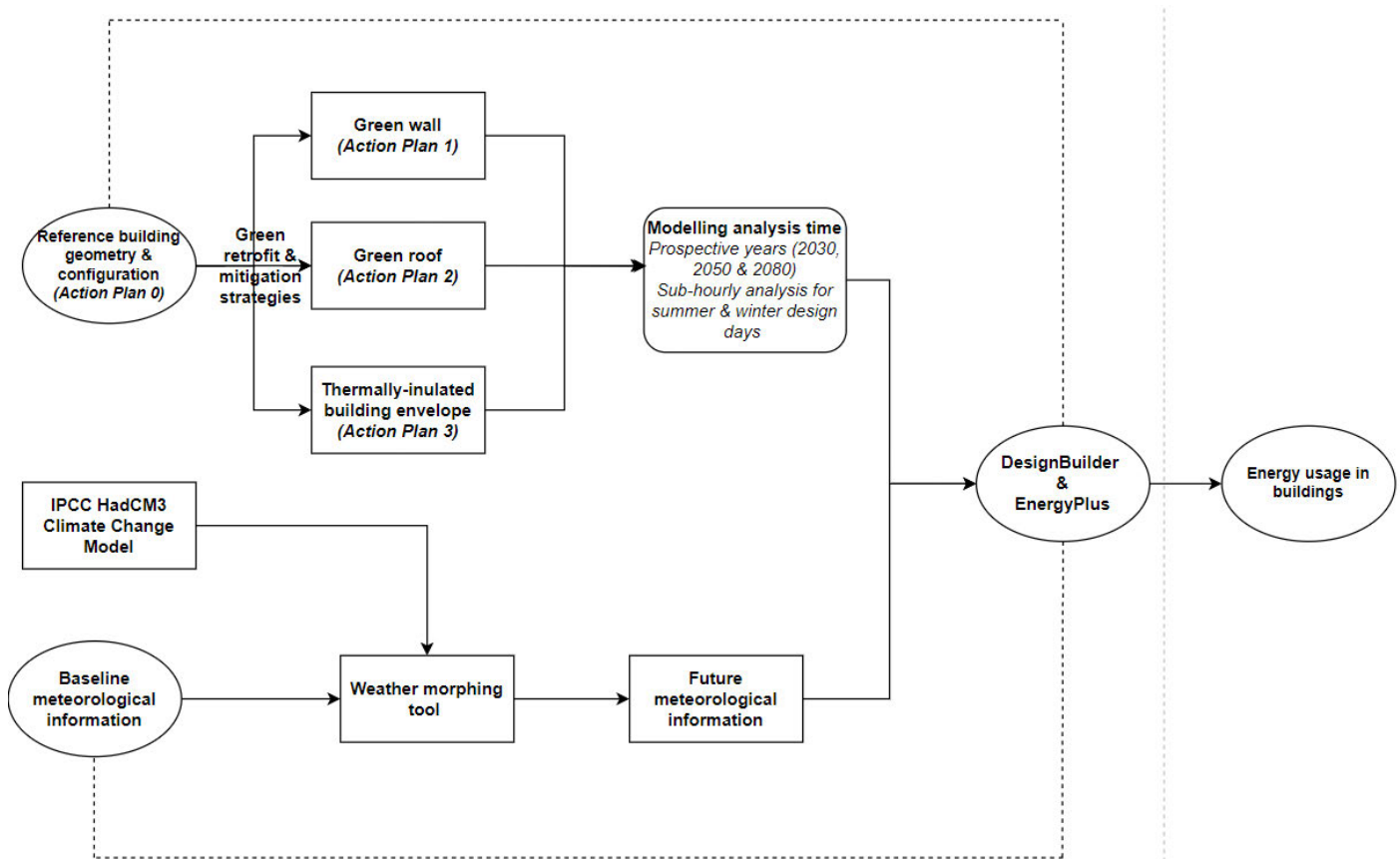
### 5.2. Research Methodology

In this study, a thorough and integrative approach that linked building energy modelling and varying climatic change was devised. The numerical parametric simulation and analysis, being a quantitative research approach was adopted as a data collection approach. Figure 5.1 illustrates the workflow of the chapter's methodology. Details about the selected study region (Durban), the building's geometry, reference weather data for future climatic predictions as well as the simulation tools and validation are demystified in the sub-sections that follow.

#### 5.2.1 Geography and climate of reference study area

This simulation-based research study was undertaken to determine the comparative effects of walls and roofs of traditional building and greenery-integrated envelopes on heat transmission through the walls and roof alongside their energy efficiency. This is implemented in a prototype low-rise institutional building block situated in Durban metropolis. Meanwhile, Durban ranks as the largest city in KwaZulu Natal province and the 3rd largest most populous region in South Africa with a population density of around 2600 people/km<sup>2</sup> and a yearly population growth rate of 0.9% (Ngcobo, Murwirapachena and Reddy 2023). Based on South African National Standards (SANS 10400XA), it is a subtropical coastal climate area with geographical coordinates of 29.8587° S and 31.0218° E

(Conradie, van Reenen and Bole 2018).

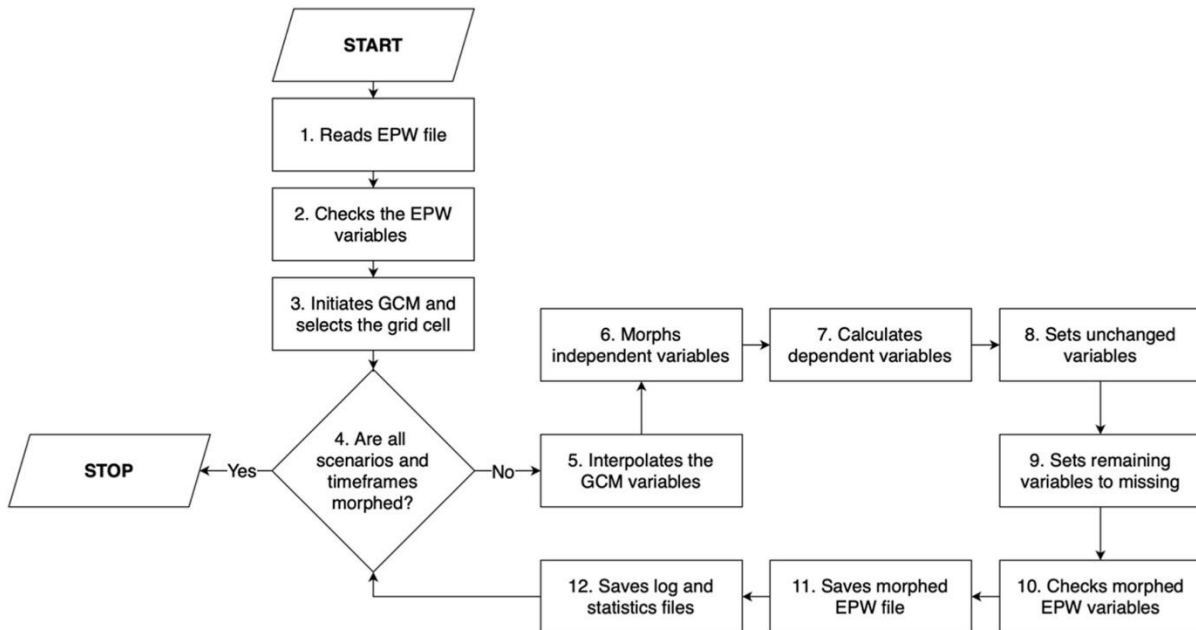


**Figure 5.1:** Flowchart for research methodology

### 5.2.2 Climate morphing and modelling

In this study, climate morphing approach was adopted to generate meteorological data that takes future climate change into consideration to analyse building energy simulations. It entails revamping a previous hourly dataset in accordance with anticipated outcomes from climate prediction models. Figure 5.2 illustrates the typical flowchart for climate modelling of any chosen region in the world. Thus, in this study, the baseline weather data that accurately capture the present weather conditions of the study area was obtained from the [climate.onebuilding.org](http://climate.onebuilding.org) website, which is a free climate-related information archive for building performance modelling (Rodrigues, Fernandes and Carvalho 2023). Durban’s weather station data was saved as an EnergyPlus Weather (EPW) format. Afterwards, a climate change model and carbon emission scenario that describes Durban’s future climatic status was selected from the A2 category of the Intergovernmental Panel on Climate Change (IPCC) database which is integrated with the Atmosphere Ocean Global Circulation Model (AOGCM) (Abe 2022). Moreover, the CCWorldWeatherGen morphing tool was chosen while the climate morphing process was conducted. The morphing tool automatically modified the weather parameters (like temperature, humidity, solar radiation, wind speed, and so on) to obtain the revamped weather dataset that depicts the prospective climate of Durban in relation to weather forecast for years

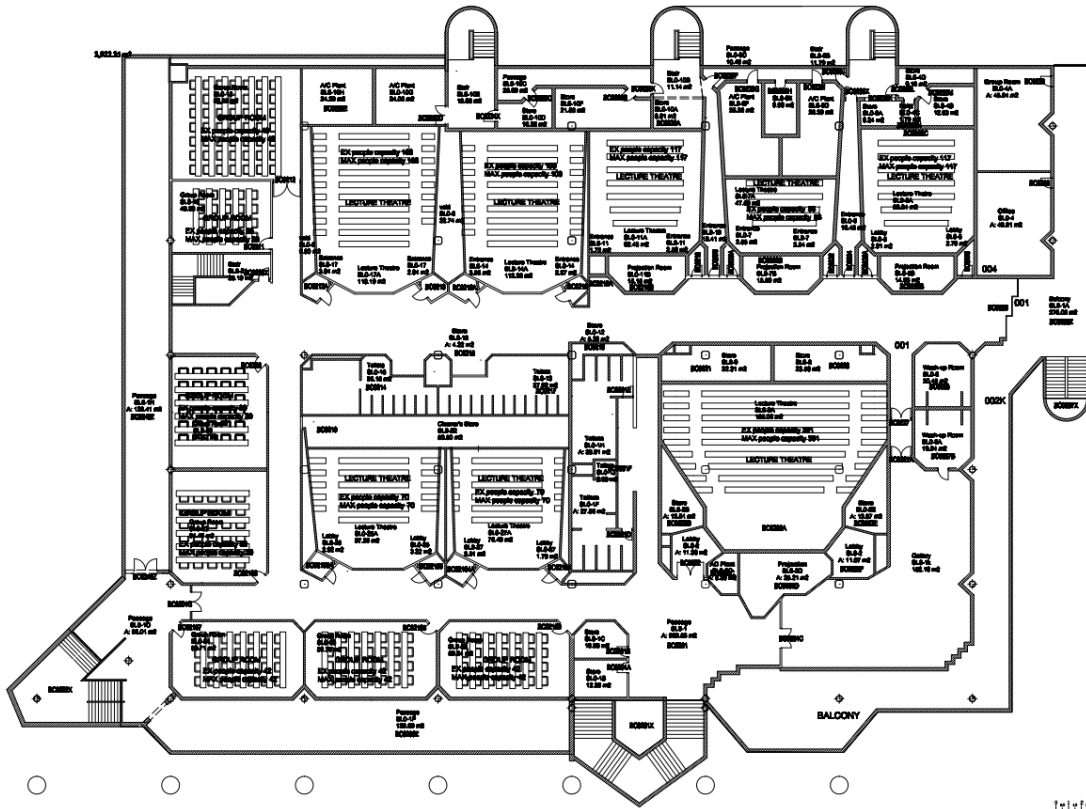
2030, 2050 and 2080. Thereafter, the baseline and future weather file were inputted to the building energy simulation software (see Section 5.2.4) for comparative analysis of the results and to evaluate the effect of climate change on energy use in buildings.



**Figure 5.2:** Climate morphing procedure for an EnergyPlus Weather information (Rodrigues, Fernandes and Carvalho 2023)

### 5.2.3 Reference building geometry and specifications

The Block C in Steve Biko Campus of the Durban University of Technology (DUT) was employed as the baseline building for this study to evaluate the energy-performance potential of building integrated greenery-based energy-saving approaches against traditional buildings. The selected building is sited in Durban, a warm temperate, fully humid and hot summer region along with cool to mild winter in South Africa. Unveiled on 27<sup>th</sup> July 1987 with geographical coordinates being 29°51'11.5" S, 31°00'20.3" E, the building is closely located to Gate 3 of Steve Biko Campus, DUT and comprises the university's Alan Pittendrigh library, writing centre, lecture theatres, students financial and services department, praying halls, the art gallery, among others. With more than 1000 seat capacity and above 100,000 volumes, the library ranks among the largest university libraries in the country. Figure 5.3 shows the building's typical floor layout plan obtained from the university's physical planning department while Table 5.1 lists out the building features and material specifications, covering a total floor area of about 3922.35 square meters.



**Figure 5.3:** Ground floor layout plan of the reference university's Block C building  
 (Source: *the university's physical planning department*)

**Table 5.1:** Component features of reference building

Building envelope component	Constituent materials	Thickness (mm)	Sun absorption	$\lambda$ (W/m-K)	Density (kg/m <sup>3</sup> )	Overall $U$ -value per component
Exterior walls	Standard insulated brick	220	0.60	0.19	700	0.464
	PUR polyurethane board	20	0.60	0.028	35	
	Gypsum plasterboard	15	0.50	0.25	900	
Interior walls	Lightweight plaster (outer)	10	0.50	0.16	600	1.054
	Uninsulated common brick	106	0.60	0.19	600	
	Lightweight plaster (inner)	10	0.50	0.160	600	
Floors	Ceramic tiles	10	0.60	0.80	1700	1.885
	Reinforced concrete	150	0.60	2.30	2300	
	Polyethylene sheet	50	0.70	0.33	920	
	Sand and stone dust	50	0.30	2.00	1950	
	Natural soil	75	0.60	1.28	1460	
Rooftop	Gypsum plasterboard	40	0.50	0.25	900	0.480
	Reinforced concrete roof slab	150	0.60	1.40	2100	
	Bituminous felt insulation	25	0.87	50	1700	
	Roof screed	100	0.73	0.41	1200	
Window	Single-glazed windows	6	n/a	0.90	n/a	2.665
	Air gap	13	n/a	n/a	n/a	
	Aluminium window frame	n/a	n/a	n/a	n/a	

$\lambda$ = thermal conductivity,  $U$ -value = thermal transmittance coefficient

Consequently, the total window to wall ratio (WWR) of the building is at 30% as defined in Equation 5.1.

$$WWR (\%) = \frac{\sum \text{Glazed window area (m}^2\text{)}}{\sum \text{Total external wall area (m}^2\text{)}} \quad \text{Eqn 5.1}$$

From the foregoing, this study formulated and employed four action plans to evaluate the possible energy-saving and climate-responsive strategies of these building-integrated greeneries (Section 2.6.2 of Chapter 2) and to contrast them with conventional buildings with little to no green retrofit measure.

Table 5.2 present an outline of these four case instances which comprise:

- i. Action Plan 0: an instance where the reference building remains bare as it is; no refurbishment at all.
- ii. Action Plan 1: this takes account of including vertical greenery system along the building façade. Here, the continuous living wall was proposedly considered to boost green building's performance efficiency. The layers that constitute the green walls are listed in Table 5.2
- iii. Action Plan 2: this takes account of including green roof on top of the building. In this case, a vegetative living roof was preferably considered as it can reduce noise, lowers stormwater runoff, provide thermal protection with little to no greenhouse gas emissions.
- iv. Action Plan 3: this takes account of including thermally-insulated green envelope materials. Addition of extruded polystyrene for insulation and airtightness was preferably considered in this scenario. Also, double-glazed windows were included as they are resistant to impact, lessen interior fading, improve soundproofing and require less heating and cooling energy demand for a comfortable indoor temperature in buildings.

## 5.2.4 Selecting and validating the building modelling software

### 5.2.4.1 Selected simulation software

The building's energy performance simulation model in this study was developed in DesignBuilder (DB) software (version 7.0.2). DB is a fully integrated simulation toolbox used to run various analysis within one modelling environment. It is an high-quality, easy-to-use simulation software that enables users to quickly access and explore the environmental performance of new and existing buildings (Lai *et al.* 2023). DB employs the EnergyPlus dynamic simulation engine to produce optimal performance simulation. Being arguably the most advanced and user-friendly building performance analysis software presently available in today's world market, the software is certified by *Agrément South Africa* for energy modelling of buildings (Greenplan 2018). This makes it an ideal tool to carry out the simulation process to achieve the chapter's objective.

**Table 5.2:** Mitigative action plans and their component properties

Mitigation strategies	Detailed outline of plant component information *	Values *
Action Plan 0 (Reference building remains bare and normal)	Nothing changes, and no green retrofit measure was made to the building structure	—
Action Plan 1 (Inclusion of green wall)  Contains layers of materials including plaster, brickwork, air space cavity, plaster, PVC, felt, soil, and flora	Plant height (m)	0.07
	Leaf area index (LAI)	5
	Leaf emissivity	0.8
	Leaf reflectivity	0.3
	Minimum stomatal resistance (s/m)	180
	Max volumetric moisture content at saturation (%)	0.3
	Min residual volumetric moisture content (%)	0.1
	Initial volumetric moisture content (%)	0.3
	Thermal conductivity (W/m.K)	0.07
	Specific heat (J/kg.K)	180
Density (kg/m <sup>3</sup> )	240	
Action Plan 2 (Inclusion of green roof)  Contains layers of materials including plaster, lean concrete mix, cement-lime mortar, bituminous felt, organic rubber, fine clay, and vegetative plant	Plant height (m)	0.6
	LAI	2.7
	Leaf emissivity	0.95
	Leaf reflectivity	0.22
	Minimum stomatal resistance (s/m)	180
	Max volumetric moisture content at saturation (%)	0.5
	Min residual volumetric moisture content (%)	0.01
	Initial volumetric moisture content (%)	0.15
	Thermal conductivity (W/m.K)	0.07
	Specific heat (J/kg.K)	180
Density (kg/m <sup>3</sup> )	240	
Action Plan 3 (Inclusion of thermally-sound green envelope materials)	Thermal transmittance coefficient (W/m <sup>2</sup> K)	0.985
	Extruded polystyrene	
	Energy-efficient double-glazed window	

\*Modified from (Lassandro and Di Turi 2017; Khotbehsara, Daemei and Malekjahan 2019)

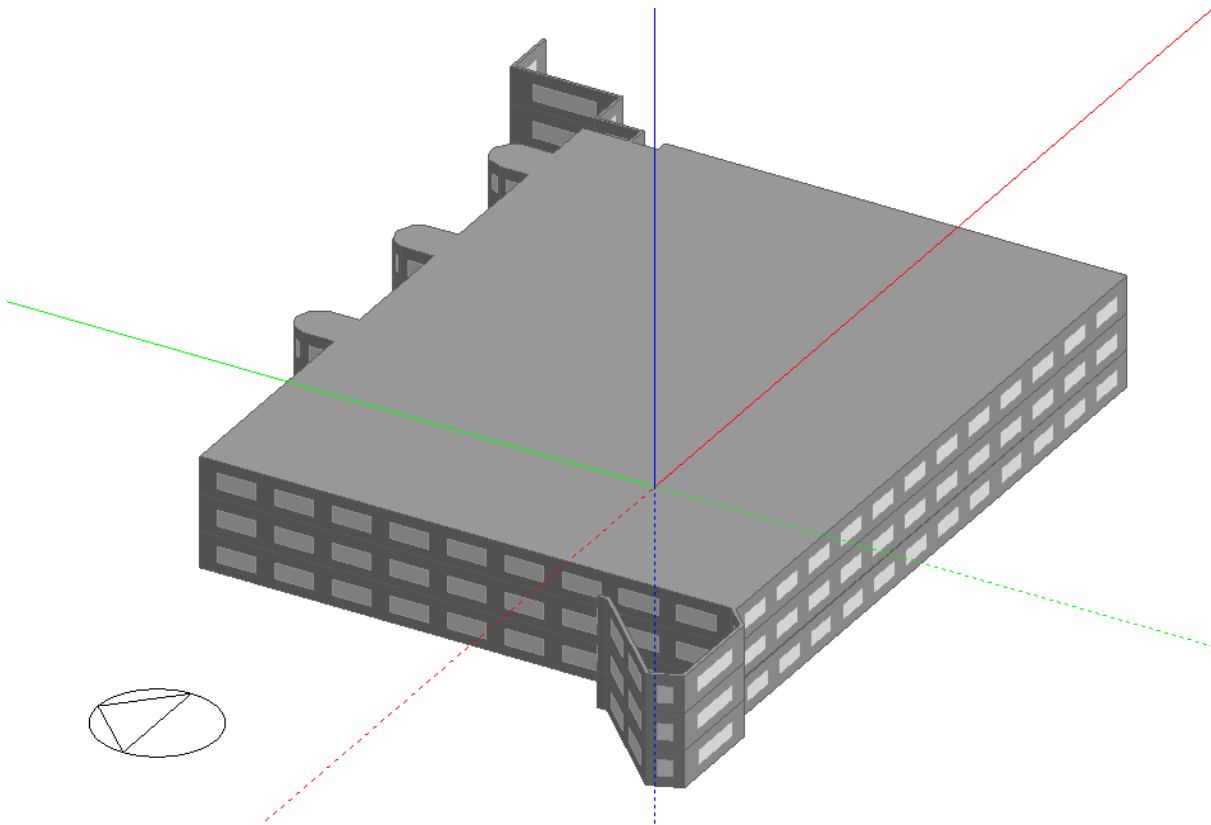
Meanwhile, Figure 5.4 shows the data objects utilized during the switch from a building information modelling (BIM) tool (Autodesk Revit) to DB engine where the energy performance analysis of the prototype building is fully implemented. In this four-stage process, the building's 2D-layout plan was re-designed in the Revit architectural software to produce a 3D model. Therefrom, a more analytical model was developed for space creation, especially in the building's closed and bounded areas. Afterwards, an energy analytical model was created to generate a green building eXtensible markup language (gbXML) file. The gbXML file was generated to foster interoperability across the DB software tool, thereby facilitating the transfer of building information recorded in CAD-based BIM tool. Finally, the gbXML file was loaded to DB for superimposition and energy performance analysis.



**Figure 5.4:** Schematic procedure of converting Revit data to DesignBuilder

#### 5.2.4.2 Building energy performance modelling

Generally, Part XA (Energy usage in buildings) of the South African Building Standards (SABS) specified that the equivalent horizontal projection distance must be maintained for buildings on either side of the glazing for altitudes facing the West, North, East, North-East, and South sectors (SABS 2013). This was considered in the modelled building which is positioned in the south-eastern direction to counter the intense solar irradiance. Figure 5.5 illustrates the generated DB model for the selected building in this study. SANS10400-XA classified the country to eight energy zones wherein Durban is situated as Zone 5H. Regarding building orientation, the standard opined that buildings in Zone 5H should be oriented to take advantage of the prevailing breezes to cool the structure naturally (SABS 2013). Thus, the modelled building is duly oriented in the south-east direction which is the ideal configuration for positioning southern hemisphere buildings that prone to southeast trade wind (Valladares-Rendón, Schmid and Lo 2017).



**Figure 5.5:** DesignBuilder 3D model for the university building.

The simulated phase investigated the heat flux by green building façade and non-green building envelopes. In the meantime, the location file containing the weather information was entered into DB while the period considered in this simulation study was a full year. The energy performance analysis utilized datasets which comprise solar heat gain, radiant temperature, ambient air temperature, relative humidity, and final end-use energy. In the meantime, some variable data is defined in accordance with how this university building really functions. Specifically, an indoor set point temperature of 23°C was selected based on extant research findings that inferred that inside temperatures set for indoor cooling range between 21°C and 25°C for office and institutional buildings in hot and humid subtropical climate zones (Han *et al.* 2019; Amoabeng *et al.* 2023).

#### 5.2.4.3 Validation of building performance simulation

While EnergyPlus is a verified simulation tool, the user is still responsible to conduct the modelling process properly. Normally, this is typically verified by correlating the simulation findings with the experimental outcomes. Nonetheless, in research without access to experimental testbeds, it is ideally imperative and feasible to check simulation results through established validation metrics. In this study, following the completion of each simulated scenario, the datasets produced by the simulations were compared using two different validation benchmark metrics namely: the mean percentage variance,  $\Delta_a$  and the standard deviation,  $\sigma_a$ . Mathematically, this are deduced as:

Mean percentage variance: 
$$\Delta_a = \frac{\sum_{b=1}^n \left( \frac{x_{a,b}}{\mu_{a,b}} - 1 \right) \times 100}{n}$$

and

Standard deviation 
$$\sigma_a = \sqrt{\frac{\sum_{b=1}^n (x_{a,b} - \mu_{a,b})^2}{n}}$$

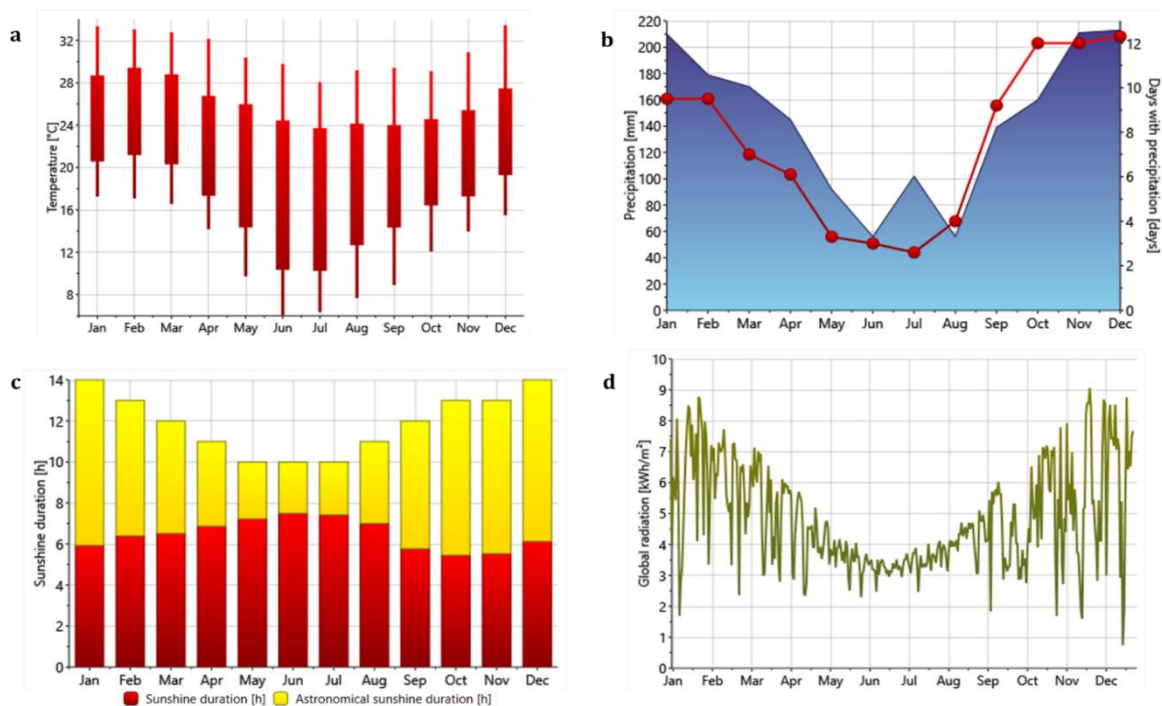
Where:  $\Delta_a$  and  $\sigma_a$  the benchmark for the  $a_{th}$  parameter that was observed, for its reference ( $x_{a,b}$ ) and future ( $\mu_{a,b}$ ) values, respectively, throughout an n-hour period. These values are presented in the results and discussion section.

### 5.3. Results and discussion

For the case study buildings mentioned earlier in the Section 5.2, the findings of the climate scenarios, long-term energy analysis and sub-hourly seasonal evaluation of the building-integrated greenery systems against the conventional building are presented and discussed in the subsequent subsections.

### 5.3.1 Analysis and discussion on the impact of potential future climatic scenarios

Results of the weather data summary for the reference year is presented in Figure 5.6. Meanwhile, to investigate how the energy requirement of buildings is being impacted by climate change of the selected location, this study simply considered four environmental parameters, namely global solar radiation, dry bulb temperature, relative humidity and wind speed. This is hinged on similar benchmarks by antecedent studies such as Andric, Kamal and Al-Ghamdi (2020) and (Khan *et al.* 2022) who utilized these variables to examine the building performance in their localities. Additionally, extant research studies alluded that these parameters are the dominant factors that invariably affect the indoor air and thermal comfort of building occupants and influence the determination of heating and cooling demands of buildings (De Masi *et al.* 2021; Baglivo *et al.* 2022). Table 5.3 presents a succinct overview of the hourly baseline and long-term meteorological data of Durban. It was observed that the global solar radiation, dry bulb (or outdoor) temperature, relative humidity and wind speed ranged from 300 – 484 Wh/m<sup>2</sup>, 16 – 24 °C, 69 – 81% and 2 – 5m/s respectively for the reference period. Meanwhile, the value range of these parameters increased marginally by up to 6% for predicted years 2030, 2050 and 2080 except for relative humidity which witnessed an abruptly decline to 9% and wind speed at 30%. This reveals that an inverse relationship exists among these environmental variables. The gradual drop in relative humidity alongside the steady rise in the solar radiation and dry bulb temperature indicate the imminent reality of climate change specifically in Durban and generally in South Africa.



**Figure 5.6:** Baseline meteorological details for study location (a) Outdoor dry bulb temperature (b) Precipitation (c) Sunshine duration (d) Global horizontal solar irradiance

**Table 5.3:** Summary of meteorological data for reference and future years

Year	Meteorological parameter	Months											
		Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Baseline	Global solar radiation (Wh/m <sup>2</sup> )	468	458	435	370	325	300	327	355	388	428	451	484
	Dry bulb temperature (°C)	24	24	24	21	19	17	16	17	19	20	21	22
	Relative humidity (%)	74	81	80	75	74	72	69	71	73	72	79	79
	Wind speed (m/s)	4	4	3	3	3	2	3	4	4	5	3	3
2030	Global solar radiation (Wh/m <sup>2</sup> )	495	462	438	385	303	294	331	398	465	465	498	497
	Dry bulb temperature (°C)	26	26	24	22	20	17	16	17	19	21	24	25
	Relative humidity (%)	74	73	75	67	74	64	71	67	74	66	68	67
	Wind speed (m/s)	2	2	1	3	2	3	4	4	4	3	2	3
2050	Global solar radiation (Wh/m <sup>2</sup> )	501	456	445	387	304	292	335	394	460	465	501	509
	Dry bulb temperature (°C)	28	27	26	24	20	19	19	21	22	24	26	27
	Relative humidity (%)	73	73	74	67	74	64	69	66	75	65	68	66
	Wind speed (m/s)	2	2	1	3	3	3	4	4	4	3	2	3
2080	Global solar radiation (Wh/m <sup>2</sup> )	512	459	444	394	305	295	330	399	473	470	501	510
	Dry bulb temperature (°C)	30	28	28	25	21	21	20	23	24	26	27	29
	Relative humidity (%)	73	73	74	67	74	64	70	65	72	65	68	66
	Wind speed (m/s)	2	2	1	3	3	3	5	4	4	3	2	3

To compare the dataset using the dual criteria mentioned earlier, the simulated weather models' results for the foreseeable future are shown in Table 5.5 alongside the values of these prominent climate variables. These values are set side by side to their reference (that is, typical meteorological year (TMY)) values in the building energy demand simulations. From the results, the average percentage difference values ( $\Delta$ ) of the dry bulb temperature are seen to have altered most noticeably from about 2% in 2030 to 8% in 2080 when compared to their baseline TMY values. For all other weather-related variables, the percentage change was much smaller as they are below 5% across all instances examined. Meanwhile, the standard deviation values ( $\sigma$ ) in all considered cases are evidently lower than 5% except for global solar radiation. These deviations could be mainly driven by a rise in the mean of the parameters considering the statistical downscaling applied to the data obtained by the CCWorldWeatherGen tool.

For further analysis of this phenomenal behaviour, Figure 5.7 displays the results of the outdoor air temperature measurements for each instance condition considered. The findings show a considerable rise in the duration of hours with thermal peaks, and temperatures exceeding 24°C. The outdoor temperature readings above 24°C occurred only over 18% of the time in the baseline (TMY) year, but this percentage substantially upsurge to 41%, 51% and 66% correspondingly in 2030, 2050 and 2080. Also, although the highest mean monthly temperature in baseline TMY was 27.7°C, the results for years 2030, 2050 and 2080 indicate values of 31.8°C, 33.2°C and 34.9°C respectively. Furthermore, the temperature pattern throughout the year shifted, with maximum values happening later in the day and across a wider range of months. For instance, as illustrated in Figure 5.6 from December through the

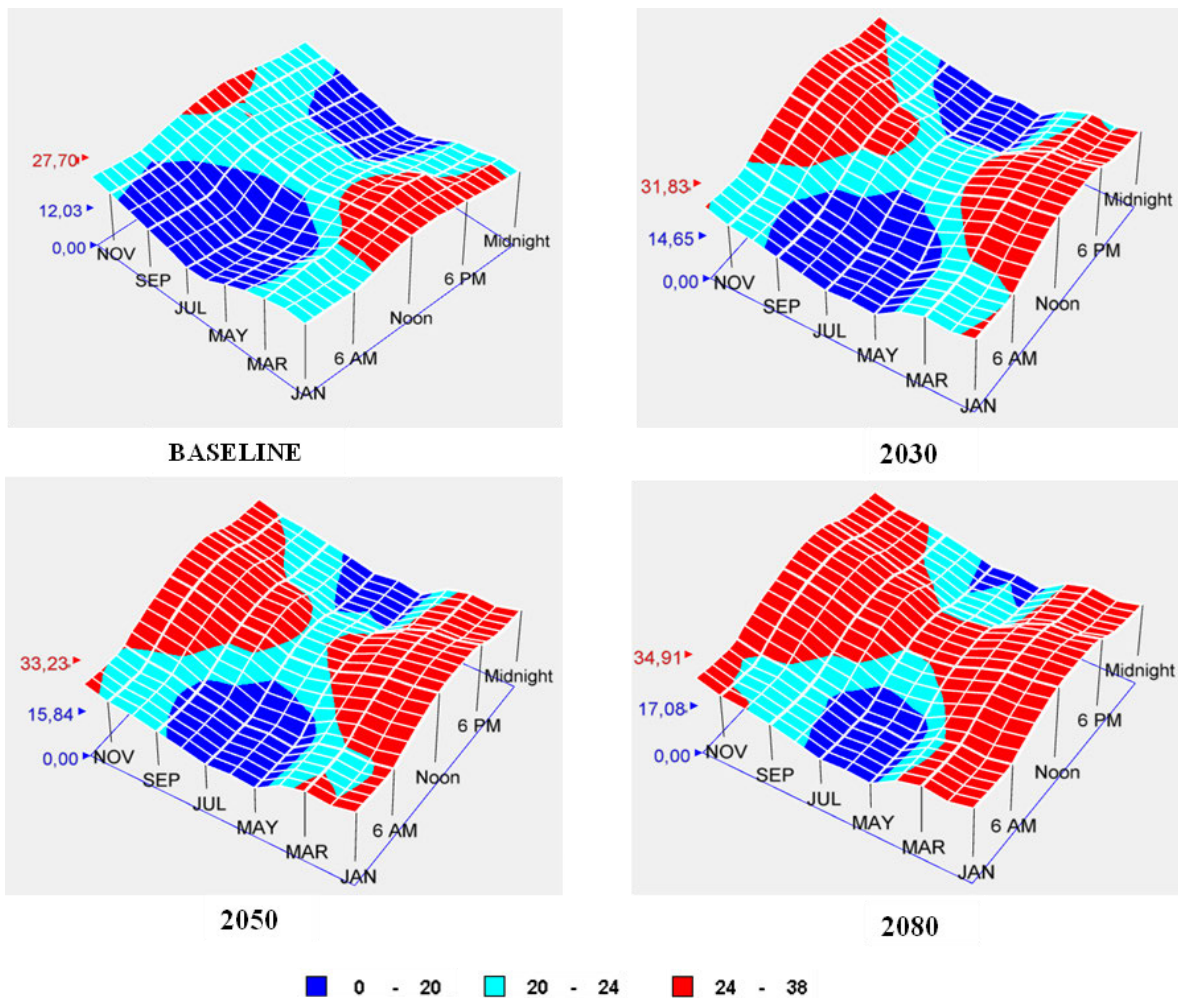
end of March of the following year, peaks under the baseline circumstances took place between 11:00a.m. and 6:00p.m. In contrast, from the mid-October of the preceding year to April's end in all of 2030, 2050 and 2080, the maximum temperatures lasted significantly longer than just the afternoon hours.

From the above narrative, it could be simply inferred that considering Durban's climate, hot thermal waves will be more intense, last longer, and reach greater temperatures in the future. Interestingly, this study's findings agreeably resonates the research of Mbokodo *et al.* (2020) whose findings surmised that the frequency of cold severe weather in South Africa will decline, while hot extreme temperatures will seriously upswing. For validation, the mean monthly temperature of 34.9°C at 2080 in this study is in concordance with earlier field study by Ncongwane *et al.* (2021) whose findings indicated a heat stress temperature condition of 35 °C for Durban coastline. In the strictest sense, South Africa may experience an annual heat wave up to 6°C between 2071 and 2090 and events involving heat waves even in winter periods are anticipated to reach the country's eastern interior where Durban is sited. Meanwhile, temperatures ranging from 32°C to 38°C are flagged under the "extreme caution" category according to the United States National Weather Service (Ncongwane *et al.* 2021) which can result in heat cramps, heat stroke, heat exhaustion and allied dire effects on humans. Under normal conditions, outdoor temperatures should be lesser than these if the ideal ambient temperature (21°C- 25°C) required for occupants' thermal comfort and productivity is to be attained. Undoubtedly, besides the global phenomenon about climate change, several other factors could have instigated this action from a local outlook. Agbajor *et al.* (2023) mentioned that rising population, industrialization, urbanization, and economic boom constitute the major reasons especially in the densely populated regions of the country. These reasons might seem genuine from the viewpoint of the quest for socialization, improved wellbeing and quality life. Nonetheless, the fact remains pitiable as they consequently threaten national environment, health, and economy. Thus, it is imperative that measures that can mitigate this imminent occurrence be immediately taken to conserve ecosystem and prolong building occupants' life quality.

**Table 5.4:** Comparative validation of meteorological parameters for forecasted years

Meteorological parameter	Benchmark	Predicted years		
		2030	2050	2080
Global solar radiation	Δ (%)	1.0808	1.1154	1.5239
	σ	6.6395	7.6158	10.0291
Dry bulb temperature	Δ (%)	1.9461	5.1315	8.1426
	σ	0.1250	0.2795	0.4640
Relative humidity	Δ (%)	0.7110	1.0058	1.1759
	σ	0.6250	1.2917	1.6667
Wind speed	Δ (%)	0.7215	1.9806	2.1948
	σ	0.0561	0.1394	0.1702

**Legend:** Δ and σ represent the mean temperature difference and the standard deviation respectively.



**Figure 5.7:** Durban's climate conditions for baseline year and prospective years

### 5.3.2 Long-term predictive energy analysis of green building greenery strategies

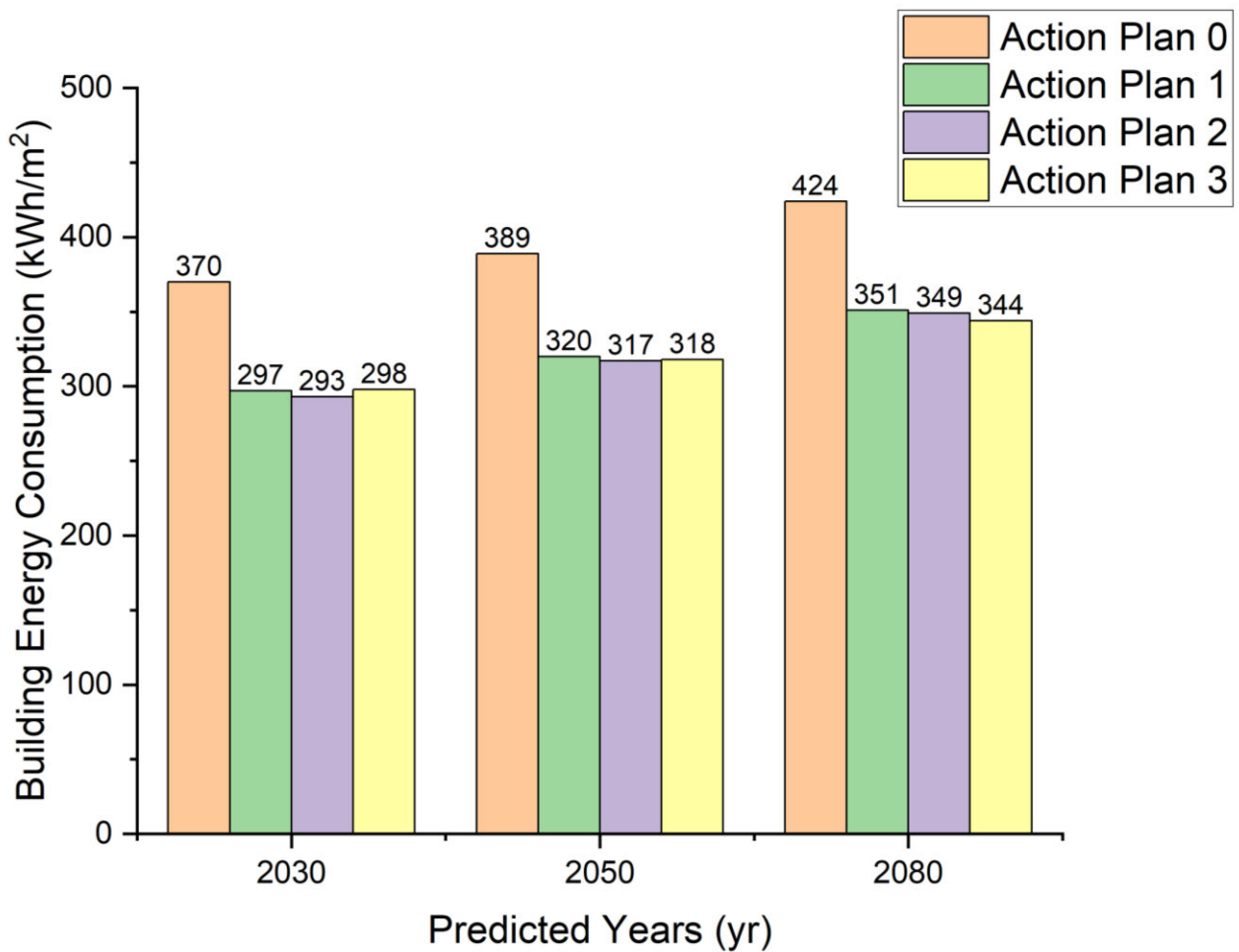
In Figure 5.8, the influence of the varying weather-related factors on buildings' energy demand for cooling alongside the aftermath of strategic climate action considered in the advocated retrofit cases in this subtropical coastal climate are described. It was revealed that in Action Plan 0 which is devoid of any responsive or mitigative solution towards climate change, the building's yearly energy use relative to the baseline year will rise by about 8%, 13% and 24% in due course by 2030, 2050 and 2080. However, by analysing the effectiveness of the other green retrofit options, it became apparent that Action Plans 1, 2 and 3 offer enhanced energy-saving potentials towards climate action in the region. Promisingly, introducing thermal insulation into the building envelope (i.e., Action Plan 3) provides more long-term positive impact than any of green wall (Action Plan 1) or green roof (Action Plan 2), even though all mitigating techniques became more effective as the dry bulb temperature rose due to climate change. As an illustration, the inclusion of green roof at the outset in 2030 lowered the energy

usage by 21% when compared to the situation in Action Plan 0, whereas energy use was reduced by less than 21% as a result of the incorporating green wall and thermal insulation for the envelope. The situation was somewhat maintained in 2050 as green roof achieved 19% energy savings while Action Plans 1 and 3 that had energy savings around 18%. However, the narrative changed at the wake of higher temperature in 2080 as the building's fabric thermal insulation yielded a 19% energy consumption reduction than green wall and green roof. Meanwhile, it is worth mentioning that in the far future (i.e., 2080), the energy usage via each of green walls, green roof and green retrofit thermal insulation at its peak is even lower than that consumed by Action Plan 0 (conventional building with no retrofit) in 2030.

Analysis of the results indicated that the application of these solution strategies proved efficacious in the studied location. By incorporating the nature-based elements of green walls and green roofs in building envelope retrofit, they will not only provide proven answers to address pending ecological issues in this densely populated subtropical area but can also act as avenues for a more sustainable and resilient urban environment in the region. Moreover, the energy use by green roof is mainly via evapotranspiration (Huang *et al.* 2023), and the photosynthetic action that occur during the growth of plants simply helps to modify the energy flux and material flow over the roof tops. As for green walls, extant field study by Hoelscher *et al.* (2016) alluded that a soothing cooling impact is attained as solar irradiance is absorbed and reflected by the plant leaves via shading effect. In view of the foregoing, the energy gained by convention in buildings within this region can be substantially lowered via these two greeneries systems. Favourably, since Durban is a subtropical coastal zone, it can enable these energy-saving mechanisms to thrive and bloom in the near future. Thus, it is no overstatement that this will provide improved impact on building energy use in this locality unlike hot, arid, and desert climates like Saudi Arabia, Kuwait, Pakistan, and whatnot.

However, the essence of introducing thermal insulation in the building fabric cannot be downplayed considering the likely adverse effects of climate change in the far future as mentioned earlier. As evidently presented in Figure 5.7, the beneficial influence of adding extruded polystyrene layer as a thermally-sound green building material can greatly lower the convective and radiative heat flux into the building's interior space. Moreover, upon addition of an ideal thickness of this building insulation material, any probable energy loss can be minimized while the building's overall thermal performance is improved. Thus, from the standpoint of a long-term comprehensive plan, the findings suggest that Action Plan 3 might be the superlative method to be applied since it surpasses both green roof and green wall in terms of energy efficiency towards the end of the 21st century and perhaps, beyond. Albeit, since all these highlighted greenery systems possess energy-saving capacities, they can invariably alter the energy budget in a positive way both yearly and in the long-term, thus providing

economic and environmental advantage.



**Figure 5.8:** Increased building energy consumption for considered action plans.

### 5.3.3 Sub-hourly evaluation of green building solution strategies under seasonal conditions

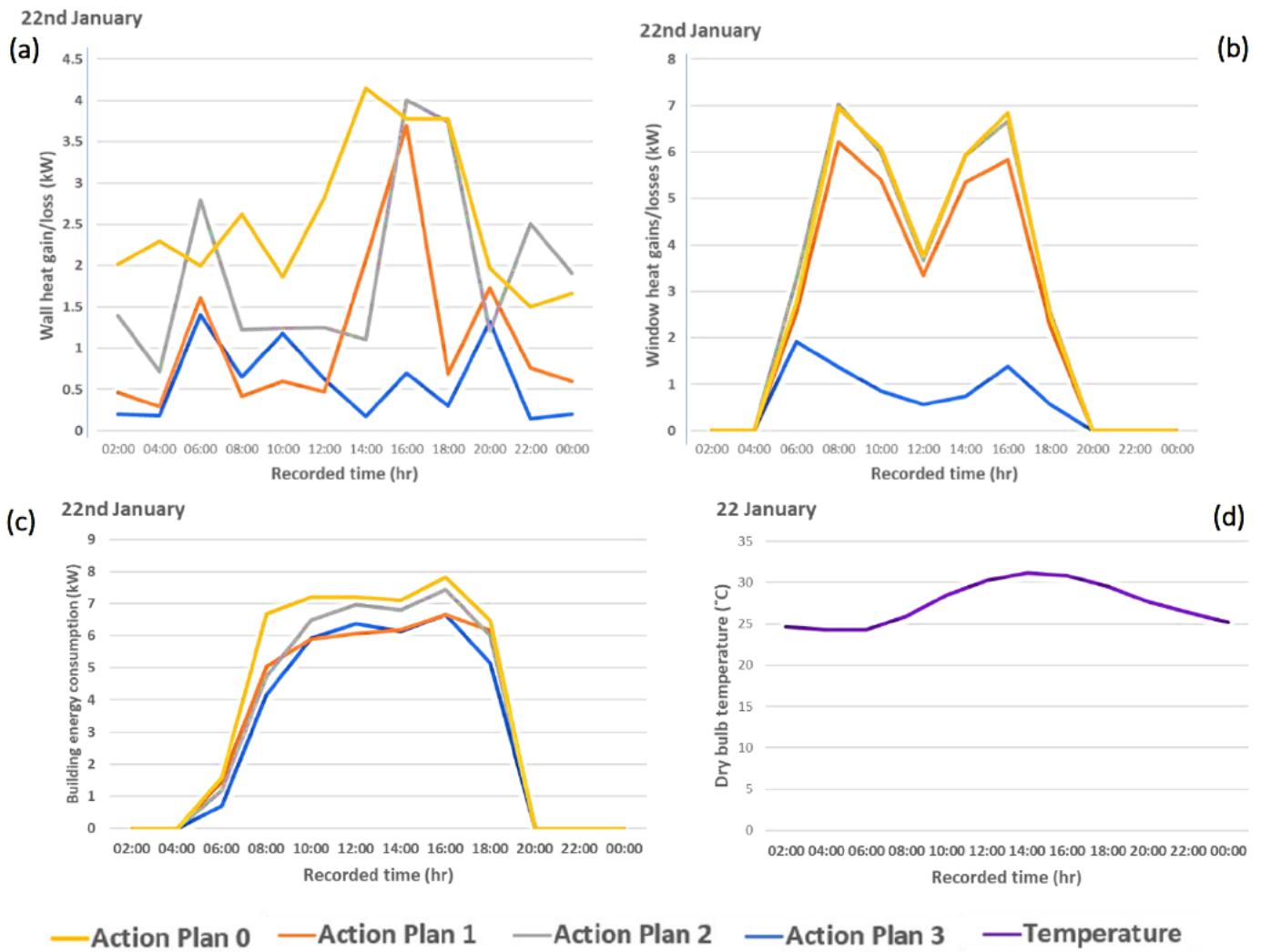
To begin with, summer and winter seasons will keep happening as long as the world exists. Thus, for more detailed understanding of the heat flux and energy use, a sub-hourly evaluation of the baseline year was conducted for a summer day and a winter day. Normally, a direct correlation usually exists between the outside temperature and internal heat gain via walls and windows. Hence, data analysis was made for the dry bulb temperature and heat transfer via these building envelopes. In South Africa, summer occurs by December, January, and February, while winter takes place from June to August. With respect to the four action plans, 22<sup>nd</sup> January and 15<sup>th</sup> July were selected as summer and winter design days respectively since they signify the peak outside temperatures during these two seasons.

#### 5.3.3.1 Summer period conditions

The graph in Figure 5.9 depicts the summertime circumstances, making it easier to observe how the solution strategies for buildings could help combat future effects of climate change in the study area. The sub-hourly analysis indicated that outdoor temperature surged towards mid-day with peak value

occurring in the afternoon around 2pm. Similarly, the results showed that leaving the case building (or any building in this region) under Action Plan 0 (i.e., no retrofitted measure) resulted in more thermal gain through windows and walls as well as more energy consumption. In contrast, green building solutions, particularly under Action Plan 3, result in building energy savings for cooling of about 1 kW for the entire day since thermal transfer (heat gains) was substantially lessened and slightly steadier all through the day than under Action Plan 1 (green walls) and Action Plan 2 (green roof). Additionally, in all cases, the release of amassed heat in the building's walls resulted in a minor increase in the heat gain at night. From the graphical results, the incorporation of an extra layer of extruded polystyrene demonstrated to have a stronger mitigation capacity, in line with the future forecasts, even if green wall and green roof only slightly lowered the energy usage for cooling the building during summer months. For Action Plans 1 and 2, there was little reduction in heat transfer via the windows, while Action Plan 3 saw roughly over 37% decrease. Additionally, equivalent findings were observed in the thermal gain through walls as Action Plan 3 had a possible extenuation capacity of about 72%, whereas Action Plans 1 and 2 had a minimal difference in heat transmission.

In sum, it could be inferred that the viability of using green walls and green roofs to address energy demand rise and as mitigation methods in this subtropical coastal climate is quite satisfactory, since the results showed a modest improvement in energy efficiency. Given that Durban's summertime temperatures are currently below 40 °C, and although future weather projections indicate that heat waves may occur more frequently and last longer, yet they may not reach the 40 °C hallmark at the close of the century. Thus, adopting green roofs and walls as strategic green building solutions could be feasible in the area. Nicely, extant research affirmed that a temperature range of 0 to 40°C is sufficient for most plants to thrive and flourish (Ewunie *et al.* 2021; Raza *et al.* 2021). However, considering the prospects of skyrocketing hot weather, the inclusion of extruded polystyrene layer and double-glazed windows as thermally-sound green building materials proved promising.



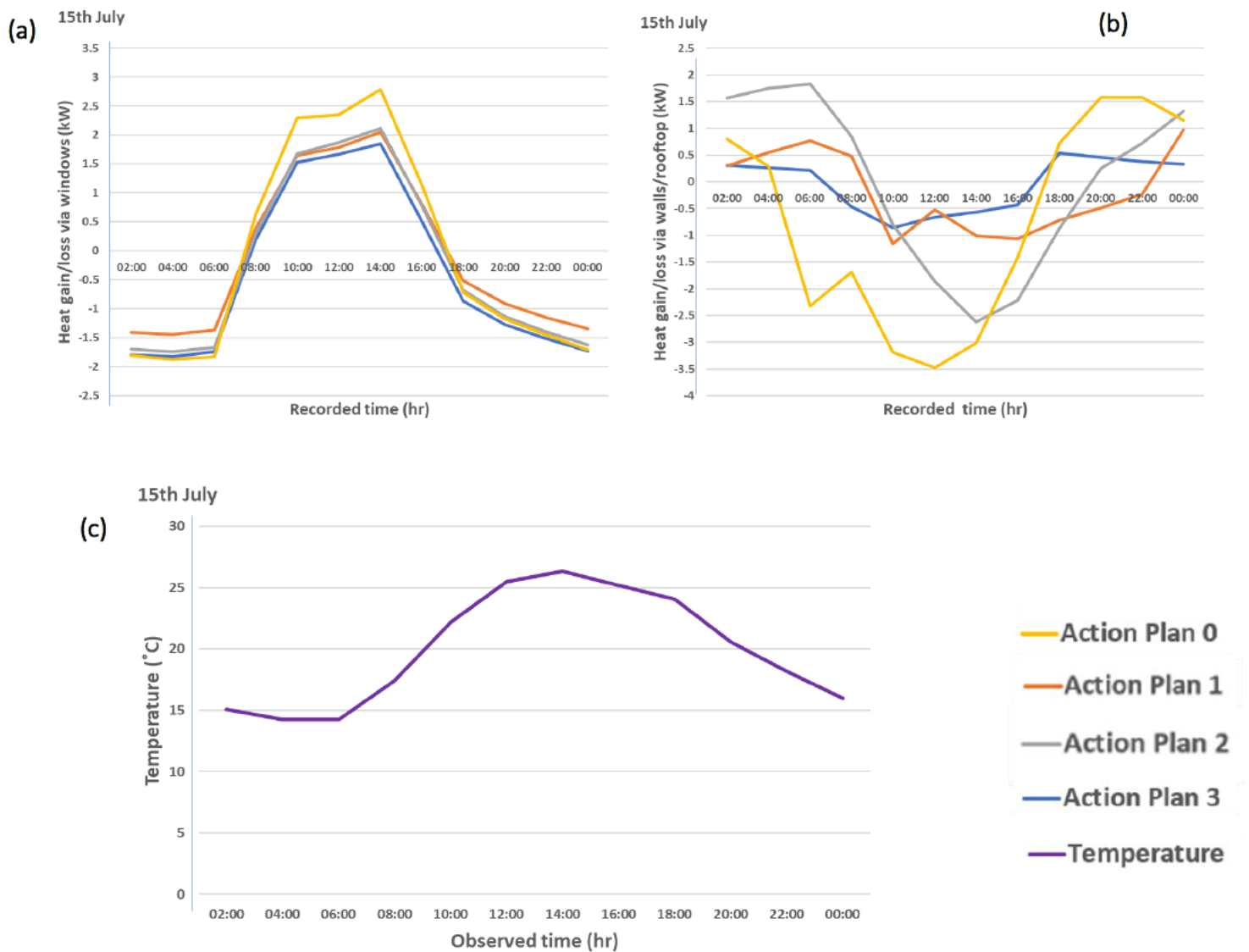
**Figure 5.9:** Sub-hourly analysis of heat flow and energy use for a typical summer day

### 5.3.3.2 Winter period conditions

The thermal situation during winter conditions is illustrated by the graph in Figure 5.10. A decreased heat flow rate was observed for Action Plan 3 (i.e., thermally insulated green envelope materials) during wintertime, with the thermal gains transfer via windows increasing from sunrise hours in all cases and peaking in the afternoon as anticipated. Compared to other action plans, the pleasant reduction in wall heat gain in Action Plan 3 (see Fig. 5.10a) could be linked to the addition of energy-efficient double-glazed windows as building components. Meanwhile, results revealed that the heat transmission via walls was negative in all the considered action plans (see Fig. 5.10b). This could be so as the designed ambient temperature (at 23°C) for the indoor comfort is higher than the outside temperature (if Fig. 5.10b were merged with 5.10c). Surprisingly, a significant heat loss is visible in Action Plan 2 (green roof) with values higher than that of Action Plans 1 and 3 and could result in more energy use required for heating purposes during winter seasons. Therefore, the greater energy losses by green roof in this study were consistent with the earlier research of He *et al.* (2020) and Huang *et al.* (2023) who found slight winter drawbacks for green roofs regarding thermal and energy

performance and alluded that the slight downsides can be simply linked to evapotranspiration from green roof. Taking this into account, a few previous studies opined that this apparent heat loss could be minimised by considering some optimal solutions. Parameters like soil thickness could be adjusted (Wei *et al.* 2021) while novel materials like blue-green roof layer (Föllmi *et al.* 2023) can be added to enhance wintertime warming of the roof's outer surface temperature. In the meantime, seeing that there is a marginal difference in the thermal loss or gain of Action Plans 1 and 3, they could be also deployed as alternative measures to contain the green roof issue during winter periods.

From the narrative results, it could be inferred that these greenery systems indicate some thermal features with respect to winter outdoor temperature.



**Figure 5.10:** Sub-hourly analysis of heat flow for a typical winter day

## 5.4 Chapter Summary and Implications

This chapter's primary objective was to assess the viability and potential of greenery systems as energy saving measures for buildings in relation to climate change within the subtropical coastal climate of the southeastern region in South Africa. Following this, a building survey and inspection were employed to select a three storey university building block out of Durban's institutional building stock to serve as the case study's representative. Three energy demand increase mitigation strategies, including the inclusion of green walls, green roof, and thermally-insulated green envelope materials, were considered alongside forecasted weather for three future years, namely 2030, 2050, and 2080.

Climate modelling findings indicate that intense heat waves will more frequently happen at greater peak temperatures in the decades to come as yearly utilization of building energy will rise during these years. Goals for green building and sustainable urban environment during these envisaged periods can be significantly aided by these greenery systems. The climate-responsive strategies proved efficacious as green walls and green roof could also allay solar heat gains during summertime while building fabric insulation outshines the former duo in terms of thermal and energy performance during wintertime.

In terms of significance, this study inferred that applying these building-integrated greenery systems in crowded metropolitan areas like Durban could alleviate the severity of urban heat island negative impact, enhance the indoor air quality and improve energy savings in buildings. Also, these greeneries can replenish the outside temperature, and benefit the city's inhabitants psychologically.

## CHAPTER 6

# Optimized energy-performance of green building-integrated photovoltaic systems (BIPV) in hot and arid regions of South Africa

### 6.1 Chapter Overview

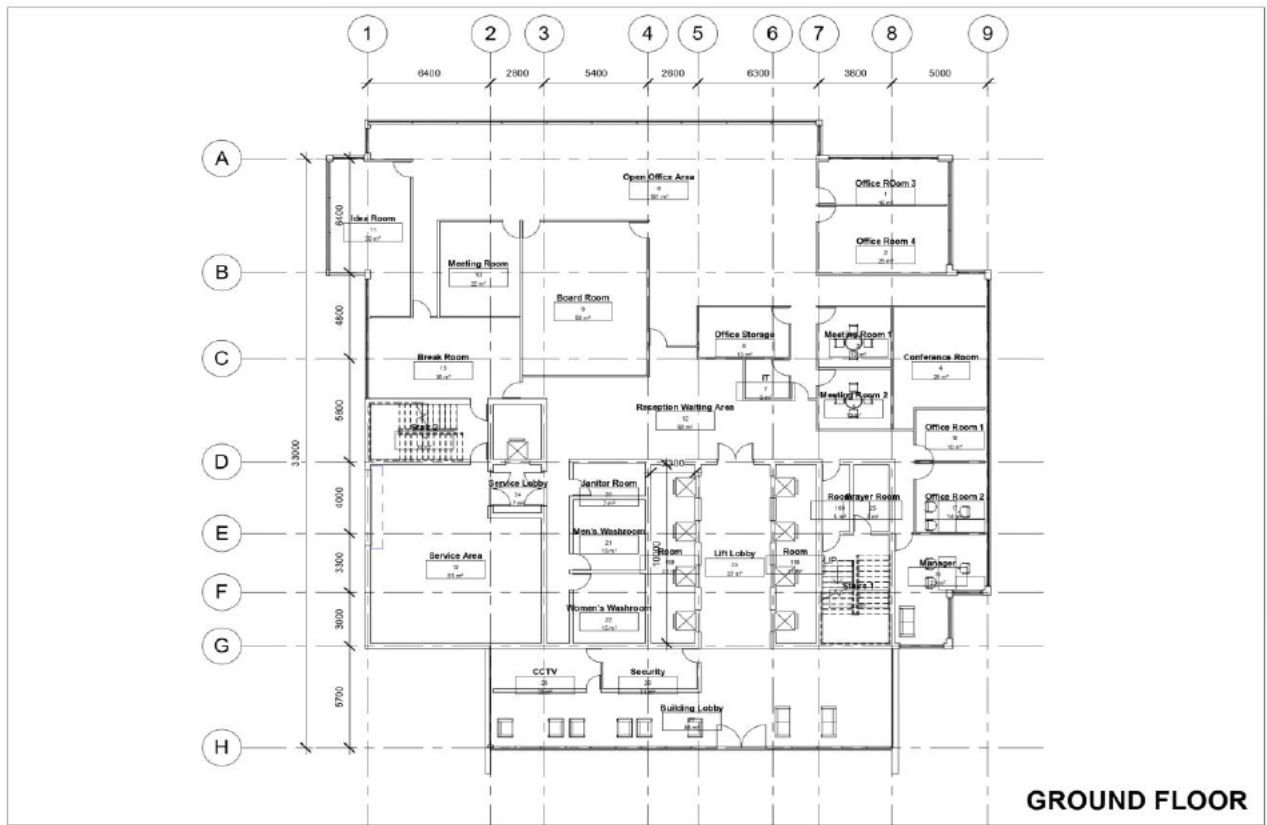
This chapter provides a performance investigation on incorporating bioclimatic renewable energy systems with existing buildings to ameliorate carbon neutrality. A literature overview on these renewable energy technologies for energy-saving in green building has been covered in Section 2.6.3 of Chapter 2. Thus, the current chapter's objective is to investigate how the energy-performance of integrating green renewable energy systems in buildings are beneficial to South Africa's hot and arid climate zones. In specifics, building integrated photovoltaic (BIPV) technology is mainly considered due to the abundance of solar energy. Therefore, Section 6.2 depicts the methods and materials adopted in conducting the research. Typically, a hypothetical model of a 5 storey office building block in the hot and arid climate zones of Nelspruit and Upington respectively, South Africa was selected as a case study for parametric simulation and analysis. The study's findings with explicit discussions are unveiled in Sections 6.3 and 6.4 while a summarized conclusion is provided in Section 6.5.

### 6.2 Research Methodology

Numerical parametric simulation is used as a data gathering method in this research, which is based on a quantitative analysis. The research tools and procedures used in this study are described in the subsections that follow.

#### 6.2.1 Building configuration and weather conditions

This study considered a typical five-storey, 25m x 20 m open-plan office building, as depicted in Figure 6.1. The structure is designed to face the four principal geographical compass points (i.e., North, East, South and West). Each storey is presumed designed to have horizontal windows, with a window area occupying around 25% of the entire floor area. Meanwhile, horizontal or vertical screens were typically employed as shading devices across windows. Also, the shading devices are considered to have a depth of around 1 m, which is identical to the depth of a typical PV panel. In all cases, it is assumed that the overall PV area is kept constant. The PV vertical spacing in horizontal shade devices is constrained by the floor height of 3.5 m, whereas vertical shading devices were ideally spaced out across the building fabric.

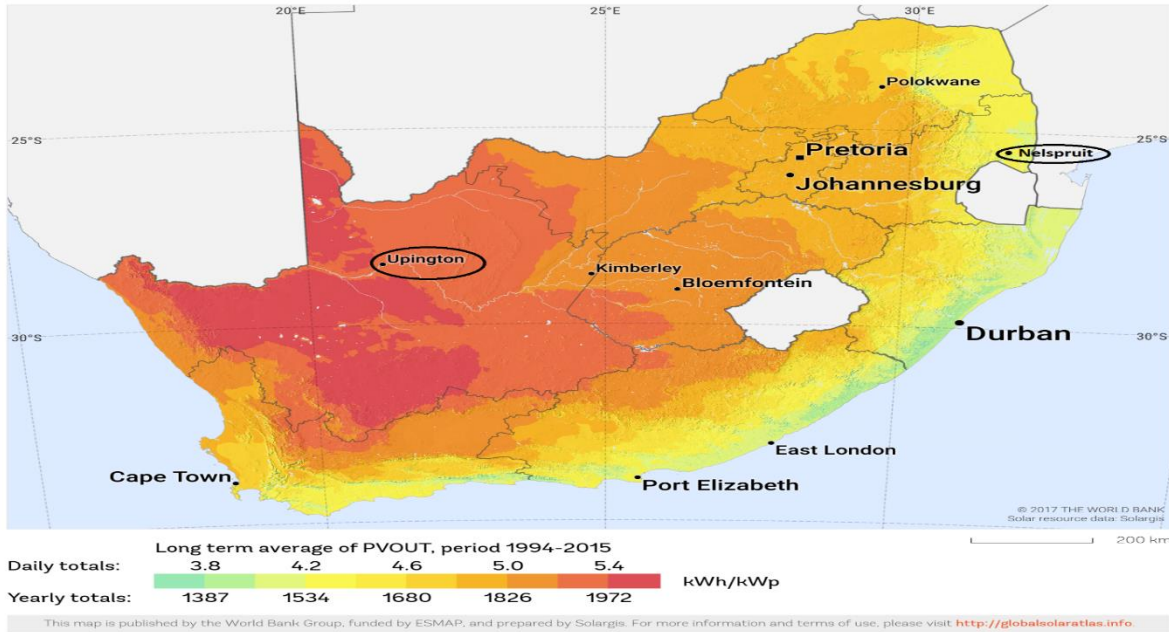


**Figure 6.1:** Ground floor plan and hypothetical model of reference office building (Source: Designed by author)

### 6.2.2 Study locations and climate conditions

Two South African cities, Nelspruit and Upington, were duly considered in this study's calculations. Nelspruit was selected being the largest city and capital of Mpumalanga province in eastern South Africa with Latitude 25.50°S and Longitude 30.91°E. Meanwhile, Upington is specifically situated at the center of the Northern Cape province with Latitude 28.41°S and Longitude 21.26°E, making it a region with very high capacity for solar energy generation as shown in Figure 6.2. Likewise, Table 6.1 summarizes the climatic conditions of these studied locations. These cities' climates are true depiction of the hot and arid weather situations of South Africa, and they correspond to two different climatic zones in Koppen's classification of climate. Due to its Cwa climate, Nelspruit has dry winters

and scorching summers with a mean daily high temperature of roughly 39°C, while Upington is known to have a hot, arid desert environment with a mean daily high temperature of roughly 40 °C due to its Bwh climate.



**Figure 6.2:** The potential of solar photovoltaic energy in South Africa\*  
\*Selected studied locations are enclosed in oval form

**Table 6.1:** Climate conditions for studied cities

Location parameters	Nelspruit	Upington
Climate Zone	Zone 3 (Hot interior)	Zone 6 (Arid interior)
Altitude	883	850
Temperature range (°C)	22 – 32	20 – 40
Humidity range (%)	19 – 45	19 – 45
Mean monthly wind speed (m/s)	2.5 – 4.5	2 – 3
Diffuse radiation (kWh/m <sup>2</sup> )	4.7 – 5.5	5.7 – 6.3

It is important to consider these regions because they depict the hottest zones in South Africa. In these two regions, the night and daytime temperatures alongside summer and winter temperatures marginally differ. The daily high temperature in winter is approximately 25 C in Nelspruit and 25 in Upington. For the analyzed cities, meteorological information from the Meteonorm 8 software was used in this study. The simulation software can create a realistic simulation for each hour of the entire year by considering the latest meteorological year climate information, which is typically based on extended periods nearing 30 years (Summa, Tarabelli and Di Perna 2021).

## 6.2.3 Parameters and case scenarios for building modelling

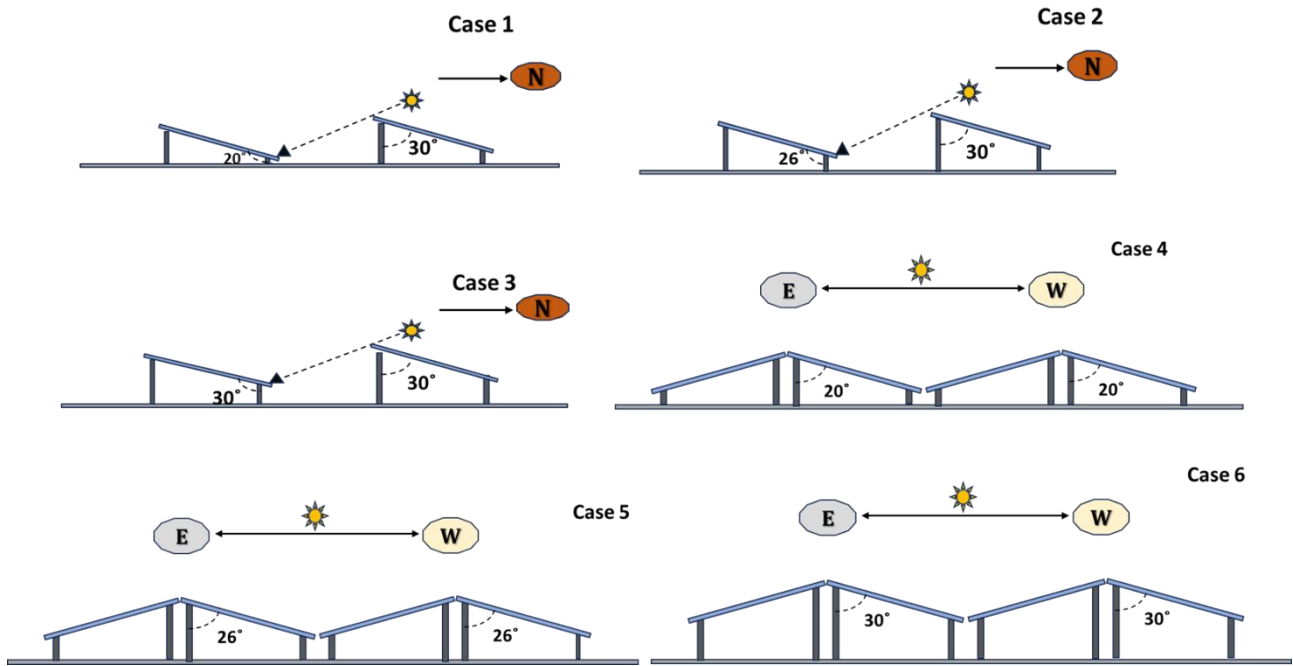
### 6.2.3.1 Independent parameters

This study considered five independent parameters that relates to the locations' weather and the BIPV system. In plain terms, the independent factors studied comprises: (i) the location's climatic status – summer and winter seasons; (ii) the BIPV's orientation coordinate at, east, north and west; (iii) the BIPV's inclination angle (iv) the installation capacity of the BIPV (v) the BIPV's installation area. Six designed cases for the BIPV layouts on buildings' rooftop are depicted in Figure 6.3 with various inclination angles, orientation angles, capacities, and overall installed areas while accounting for the distance among the BIPV panels.

In this study, three adjustable inclination angles (20°, 26° and 30°) for the BIPV modules' arrangement in both Upington and Nelspruit were proposed considering the latitude of both locations. The 26° inclination angle was selected because it depicts the ideal average inclination angle for both locations. By positioning the BIPV modules perpendicular to the yearly average solar path, this angle can help in maximizing the annual energy production and offers both regions an equitable energy production. Meanwhile, the 20° inclination angle was selected to allow for installation of more BIPV panels. Also, this lower angle can enhance the energy output during summer months for both regions by allowing the modules to absorb a greater amount of light when the sun is at a higher angle. Conversely, an increased inclination angle of 30° was finally chosen to allow for optimal energy production during winter seasons when the sun is at a lower angle and the sunlight intensity drops. Additionally, this angle is suggested as the optimum tilt angle for most South African locations in order to capture the utmost solar insolation possible (Le Roux 2016). In the meantime, this study considered the northward orientation to enable the BIPV panels to capture the utmost direct sunlight and optimize their potential of generating energy. However, the east-west orientation was chosen to allow for the flow of electricity generation during the day to be more evenly distributed by the BIPV panels (Le Roux 2016; Yadav *et al.* 2021).

### 6.2.3.2 Dependent parameters

To find out the effects of the analysed BIPV systems on solar energy harvesting, potential, and energy savings, two dependent parameters were considered in this study. These include: (i) the BIPV module type and (ii) the distance between the BIPV panels. The BIPV module type could be monocrystalline, polycrystalline, or thin-film. In this study, the monocrystalline silicon BIPV module was employed in all cases because of its relatively great efficiency and dependability (Alhammadi *et al.* 2022).



**Figure 6.3:** The six considered case scenarios for the hypothesized residential building model

#### 6.2.4 Estimation of energy usage

Based on earlier surveys and studies, the typical yearly energy use for office buildings has been calculated to compare energy production and consumption. A South African office building's annual energy use intensity was estimated to be about 250 kWh/m<sup>2</sup> (Udosen *et al.* 2022), while earlier research revealed that almost 70% of households with low incomes rely on fuels (such as firewood) besides electricity to meet their essential energy requirements (Bohlmann and Inglesi-Lotz 2018). Recent estimations alluded that the average commercial building used about 6000 kWh of power per month, and 51% of domestic residences and small sized office spaces used less. (Besada 2022) Similarly, based on the South African Energy Sector Report 2021, each office or commercial building stock consumes 2350 kWh of electricity on average per month. In light of this, it is presumptive that a normal office building uses about 45000 kWh of electricity annually.

In this study, the current energy usage alongside the yearly rise of electricity consumption were employed to compare the generated power and consumption over the course of the BIPV system's life. It is predicted that in upcoming years to around 2030, power usage by office buildings will increase gradually by 7% which will be propelled by several factors, such as population increase, urbanization, climate change, economic status, electrification rates, and energy prices (Besada 2022; Agbajor *et al.* 2023).

### 6.2.5 Selected simulation tool

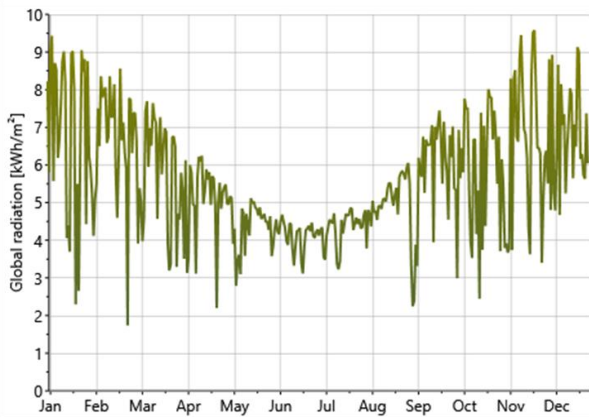
The operational efficiency of shading devices employed as BIPVs is explored by utilizing computer modelling to fulfil the intended parametric modelling. In this regard, numerous trusted and verified building energy modelling tools like Polysun DesignBuilder, OpenStudio, BEopt, eQuest and Green Building Studio are accessible (Kamel and Memari 2019). A simulation engine and a graphical user interface (GUI) are two possible components of some of these tools. In this study, Polysun software was selected since it is an excellent tool for designing, simulating, and maximizing energy systems for buildings, as well as for residential and commercial sectors and has an intuitive GUI interface. It is a highly dependable and expert simulation tool. For the design, sizing, and optimization of heat pumps, photovoltaic and solar thermal systems, cogeneration units, and integrated systems (Yang *et al.* 2023). It is capable of precisely estimating the costs associated with feeding and maintaining various systems on a monthly and annual basis. Additionally, it integrates applications smartly to meet demands for heating, cooling, power, and electromobility. With solid findings for functionality, energy efficiency, and profitability from single-family houses to entire districts, globally, and for all market-standard technologies, it delivers a multi-practice simulation for various energy systems (Berrabah *et al.* 2022).

## 6.3 Results and Discussion on Energy Performance of Green BIPV

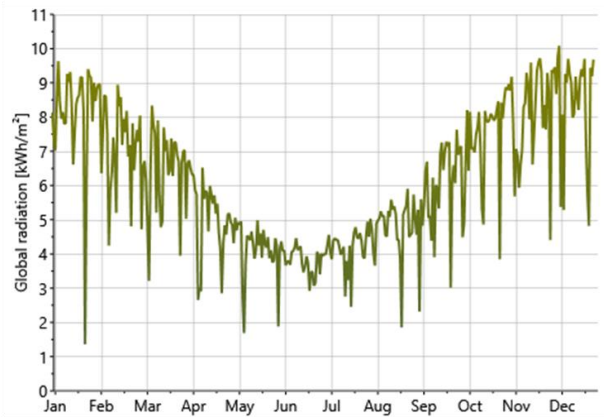
For the case study buildings mentioned earlier in the preceding part, the findings of the energy of the BIPV systems are presented and discussed in the subsequent subsections.

### 6.3.1 BIPV energy analysis and findings

Using the Polysun simulation software, the BIPV power generation installed on residential buildings' rooftops were estimated. The results of the daily global horizontal irradiance (GHI) for a typical year in the studied cities are presented in Figure 6.4, It was observed that the GHI average value reaches around 9.0 kWh/m<sup>2</sup> in Nelspruit and up to 9.2 kWh/m<sup>2</sup> in Upington in summer seasons. Meanwhile, during winter periods, the daily GUI average values for Nelspruit and Upington are about 4.8kWh/m<sup>2</sup> and 4.7 kWh/m<sup>2</sup> respectively. This shows that these two cities are marked by a great degree of GHI.



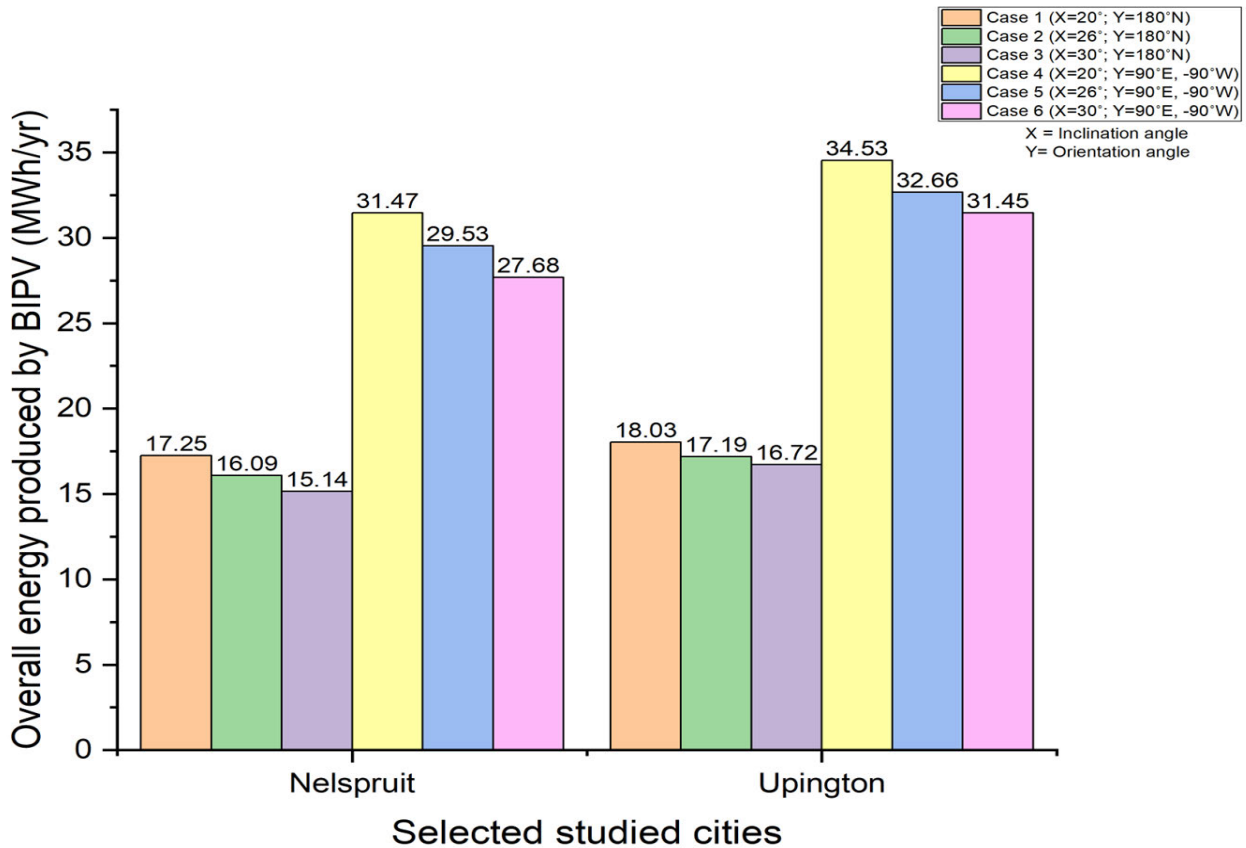
Nelspruit



Upington

**Figure 6.4:** Global horizontal irradiance for the study locations

Figure 6.5 illustrates the study results on the total quantity of power generated annually by the BIPV panels for residential buildings in the Nelspruit and Upington. The greatest energy generation in the surveyed cities occurred under Case 4 whenever the BIPV modules were aligned in the east-to-west direction and inclined at  $20^\circ$  with 34.53 MWh/year in Upington and 31.47 MWh/year in Nelspruit. The next-highest quantity of energy generated is achieved by the BIPV modules with a  $26^\circ$  inclination angle and positioned in the east-west orientation (Case 5). Here, the total energy produced for the hypothesized buildings is 32.66 MWh/year in Upington and 29.53 MWh/year in Nelspruit. Similarly, the values in Case 6 were ranked third as the overall power produced in Nelspruit and Upington are 31.45 MWh/year and 27.68 MWh/year respectively. In this case, the BIPV panels were placed at an increased tilt angle of  $30^\circ$ . However, whenever the modules are inclined at  $20^\circ$  and  $26^\circ$  northwards, energy generated by these modules was 17.25 and 16.09 MWh/year for Cases 1 and 2 respectively in Nelspruit. The power generation amounted to 18.03 MWh/year and 17.19 MWh/year for Cases 1 and 2 respectively in Upington. Apparently, the least amount of electricity is generated in Case 3 with 16.72 and 15.14 MWh/year in Upington and Nelspruit respectively when the BIPV modules are tilted at  $30^\circ$ , facing the north. As illustrated in Table 6.2, analysis from the study showed that based on the three inclination angles considered ( $20^\circ$ ,  $26^\circ$  and  $30^\circ$ ), some marginal drops occurred in the energy produced via the BIPV modules for the domestic buildings in both cities. The percentage difference spanned between 6% to 12% and 3% to 7% for Cases 1 to 3 when these panels are oriented northwards in Nelspruit and Upington respectively. Similarly, in Cases 4-6 when the BIPV modules are oriented in the east-west split, the percentage decline in energy production ranged from 6% to 12% in Nelspruit and about 4% to 9% in Upington



**Figure 6.5:** BIPV energy production (MWh/yr) for residential buildings in all cases

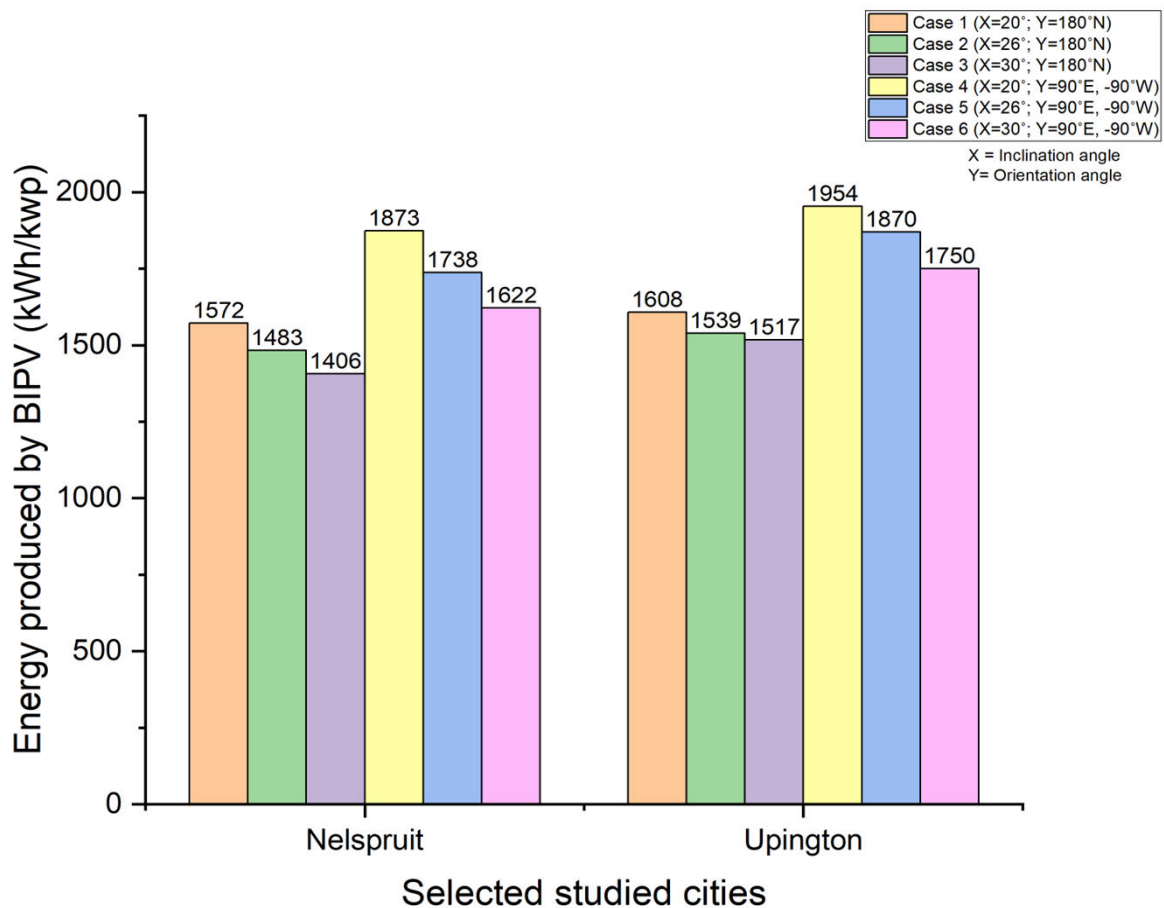
However, from the outlook of the considered orientation angles (East-west vs North direction) the electricity generated by the BIPV modules significant declined at higher percentages. As shown in Figure 6.2, this percentage decrease is roughly between 45% to 48% in all considered cases with the same inclination angles but in different orientations. For instance, comparing Case 1 and Case 4 with similar tilt angles (20°) but different orientations (northwards for Case 1 and east-west for Case 4), the percentage drop is 45.19% and 47.79% for Nelspruit and Upington respectively. The same applies to the remaining cases when compared together.

**Table 6:** Percentage drop in annual energy produced by BIPV modules

Conditions	Orientation	Cases considered	Percentage drop in energy generated by BIPV modules	
			Nelspruit	Upington
Based on inclination angles (20°, 26° and 30°)	Northwards	Δ (Case 1 - Case 2)	5.63%	4.66%
		Δ (Case 2 - Case 3)	5.90%	2.85%
		Δ (Case 1 - Case 3)	12.23%	7.26%
	East-west direction	Δ (Case 4 - Case 5)	6.26%	5.42%
		Δ (Case 5 - Case 6)	6.16%	3.70%
		Δ (Case 4 - Case 6)	12.04%	8.92%
Based on orientation angles	East-west direction vs Northwards	Δ (Case 4 - Case 1)	45.19%	47.79%
		Δ (Case 5 - Case 2)	45.51%	47.37%
		Δ (Case 6 - Case 3)	45.30%	46.84%

In the meantime, the energy output for building per installed kilowatt peak power output (kWp) is

shown in Figure 6.6. When the BIPV modules are installed with their faces along the east-west split, the highest energy production per kWp is obtained with the lowest inclination angle, (which is 20° in this study), achieving values around 1954 kWh in Upington and 1873 kWh in Nelspruit. This is trailed by Case 5 (26° tilt angle at east-west direction) with 1870 kWh/kWp and 1738 kWh/kWp in Upington and Nelspruit respectively. However, the quantity of energy generated with the best inclination angle of 30° occurs when the BIPV modules are mounted towards north, with the higher output of about 1517 kWh/ kWp in the arid region of Upington and followed by a value around 1406 kWh/ kWp in the hot climatic area of Nelspruit. Moreover, the results revealed that whenever the inclination angle is set to 30° and the rooftop BIPV modules are oriented towards east-west direction, Case 6 produced the least amount of power per installation in any of the situations. In this case, the BIPV electrical energy generation is at 1750 kWh/ kWp and 1622 kWh/ kWp for Upington and Nelspruit respectively.

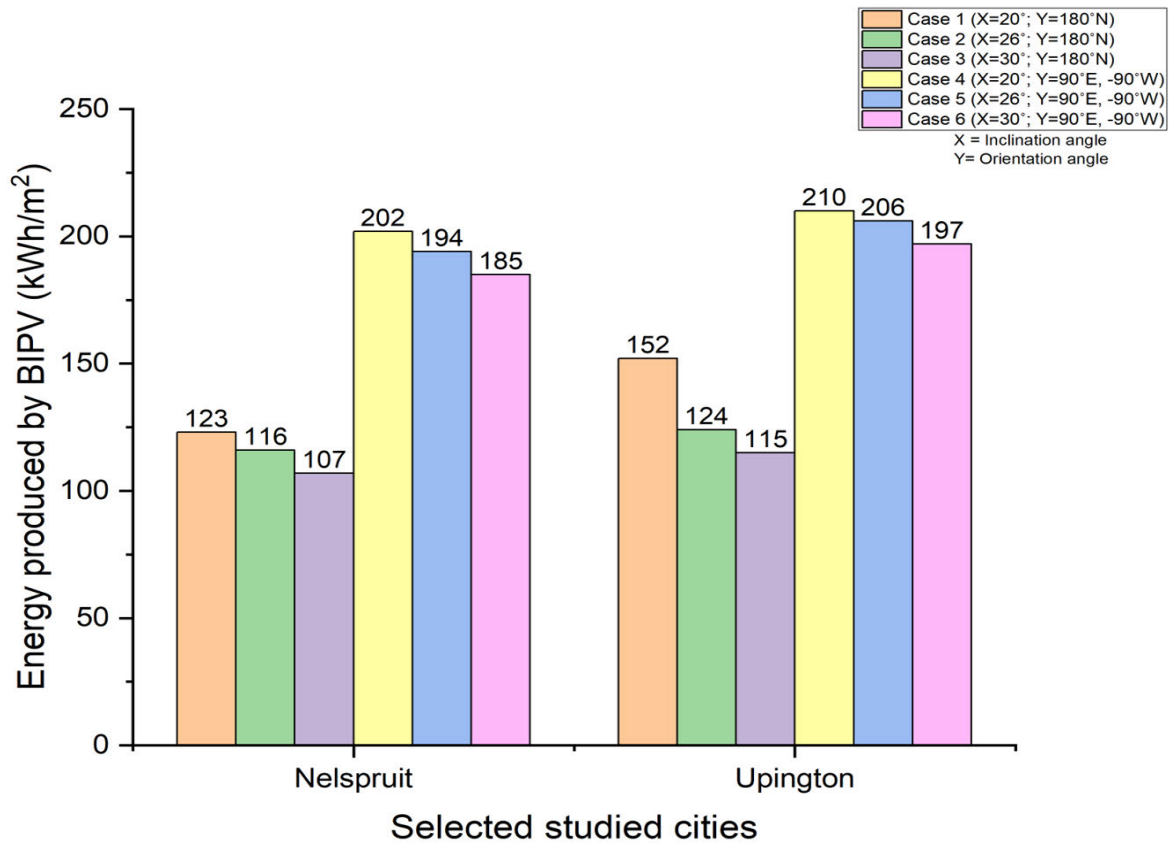


**Figure 6.6:** BIPV energy production (kWh/kWp) for residential buildings in all cases

When analysing the amount of overall energy generated with the amount of energy generated per kWp in each scenario, the findings indicated that when the BIPV is oriented northwards (Cases 1, 2 and 3), Case 1 with the smallest inclination angle produces more overall electric power, despite the fact the amount of power generated per kWp is lesser. This occurred because Case 1 has the highest installation potential in this aspect. In contrast, the overall amount of power supplied is greater in

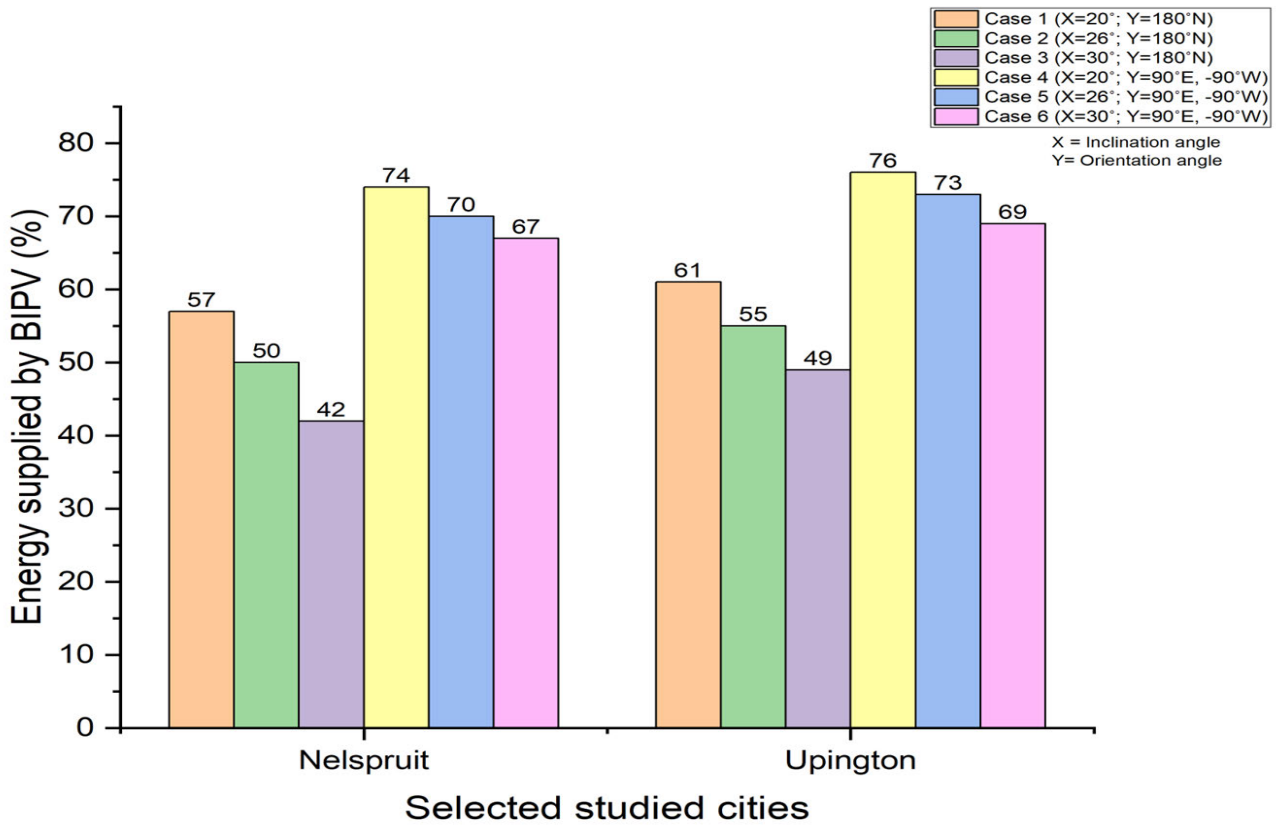
Case 4 even if the total installed capacity is lower when the BIPV modules are oriented towards east-west direction (Cases 4, 5 and 6). This is so, the reason being that as the BIPV modules capture more sunlight through lower inclination angles, more power is generated per kilowatt peak.

Moreover, this study's analyses were expanded by determining the energy output per unit area of the usable rooftop space for the installation of BIPV modules. As depicted in Figure 6.7, when the BIPV modules were set up over all the building's rooftop in the east-west orientation and lower inclination angle, it produced higher total power generation than the optimum inclination angle ( $30^\circ$ ) and north-facing BIPV modules. In this scenario, energy output per area in Cases 1 and 2 yielded  $123 \text{ kWh/m}^2$  and  $116 \text{ kWh/m}^2$  in Nelspruit, whereas this resulted in  $152 \text{ kWh/m}^2$  and  $124 \text{ kWh/m}^2$  in Upington. Likewise, whenever the BIPV modules are positioned at the ideal inclination angle of  $30^\circ$  and north orientation, the modules at Case 3 generated the least amount of energy in buildings, with the overall power/ $\text{m}^2$  of rooftop space being  $135 \text{ kWh}$  in Upington and  $107 \text{ kWh}$  in Nelspruit. Conversely, in Case 4, the BIPV modules' best electricity output is attained in the office building when they are mounted with a  $20^\circ$  inclination angle towards east-west. This yielded  $210 \text{ kWh/m}^2$  and  $202 \text{ kWh/m}^2$  of the building's rooftop space in Upington, and Nelspruit respectively. These values are lagged by Cases 5 and 6 with  $194 \text{ kWh/m}^2$  and  $185 \text{ kWh/m}^2$  in Nelspruit, and  $206 \text{ kWh/m}^2$  and  $197 \text{ kWh/m}^2$  in Upington. Meanwhile, minimal percentage reductions are evident in the energy output/ $\text{m}^2$  based on the three inclination angles ( $20^\circ$ ,  $26^\circ$  and  $30^\circ$ ). Contrariwise, from an orientation angle perspective, substantial drops in the energy produced per unit area are obvious as shown in Figure 6.7.



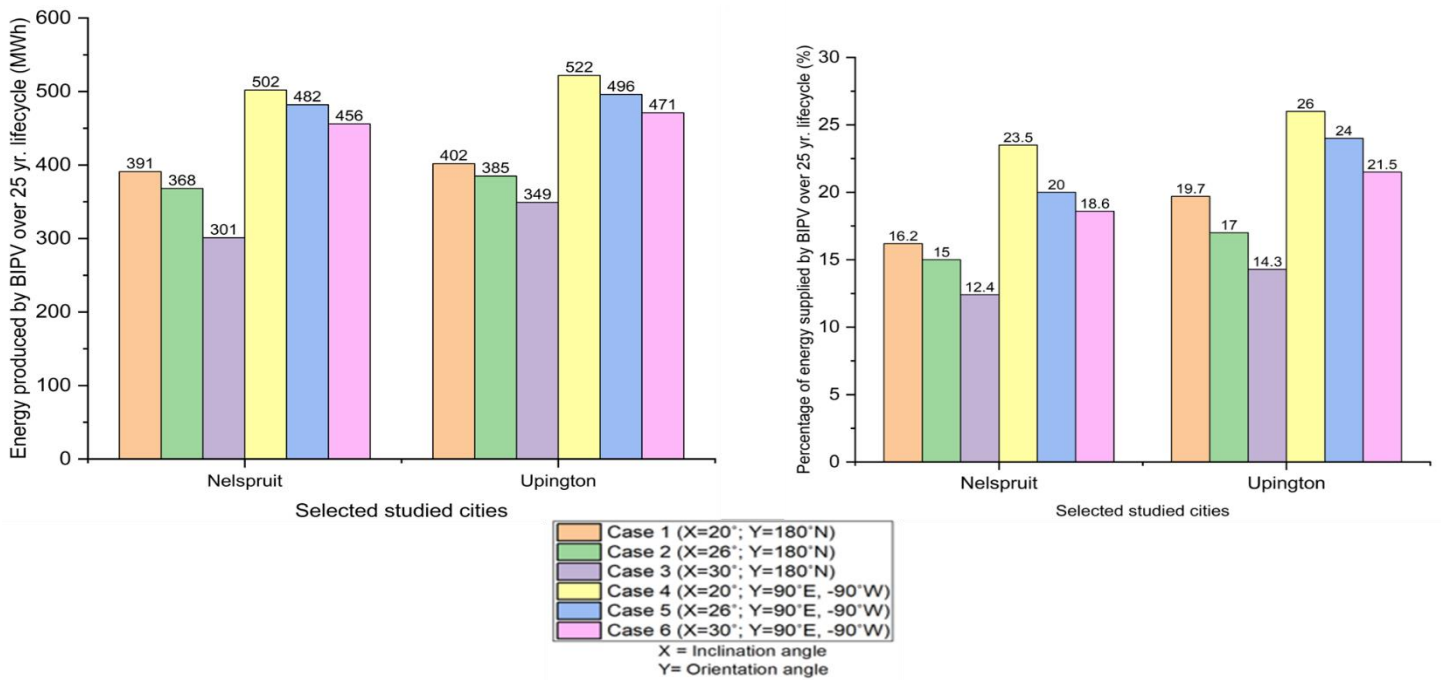
**Figure 6.7:** BIPV energy production (kWh/m<sup>2</sup>) for residential buildings in all cases

As revealed in Figure 6.8, the comparative analysis of energy production and consumption showed that the energy produced by BIPV modules may meet as much as 76% and 74% of the present energy needs of Upington, and Nelspruit respectively. This indicates that the maximum values for the two studied cities were attained under Case 4. These were closely trailed by Cases 5 and 4, each attaining 70% and 67% in Nelspruit as well as 73% and 69% in Upington. In these three cases, the BIPV modules are veered towards the east-west direction. However, when these modules are positioned northwards at 20°, 26° and 30° inclination angles, the percentage in produced and utilized energy by the BIPV modules reduced further. In Cases 1 and 2, these values were 61% and 55% in Upington while they attained 57% and 50% in Nelspruit. Overall, these percentages were lowest in Case 3 having obtained 42% and 49% in Nelspruit and Upington respectively.



**Figure 6.8:** Current percentage of energy demand supplied by BIPV

Also, for the 25-year lifecycle, the projected power production from BIPV systems and the proportion of provided energy need were determined (see Figure 6.9), with due consideration of rising electricity demand and the declining efficiency of the BIPV systems.



**Figure 6.9:** Energy produce by BIPV over lifecycle

### **6.3.2 Further Discussion of BIPV Energy Analysis Results**

In this study, the analysis above has comparatively demystified BIPV effectiveness in terms of energy performance and efficiency. It was discovered that implementing BIPV systems in these two regions is a potential and long-term technique for reducing rising energy demand by buildings and greenhouse gas emissions. Meanwhile, the results revealed the major factors which influence the optimal energy performance of these promising technology in the two selected studies. These are elucidated below.

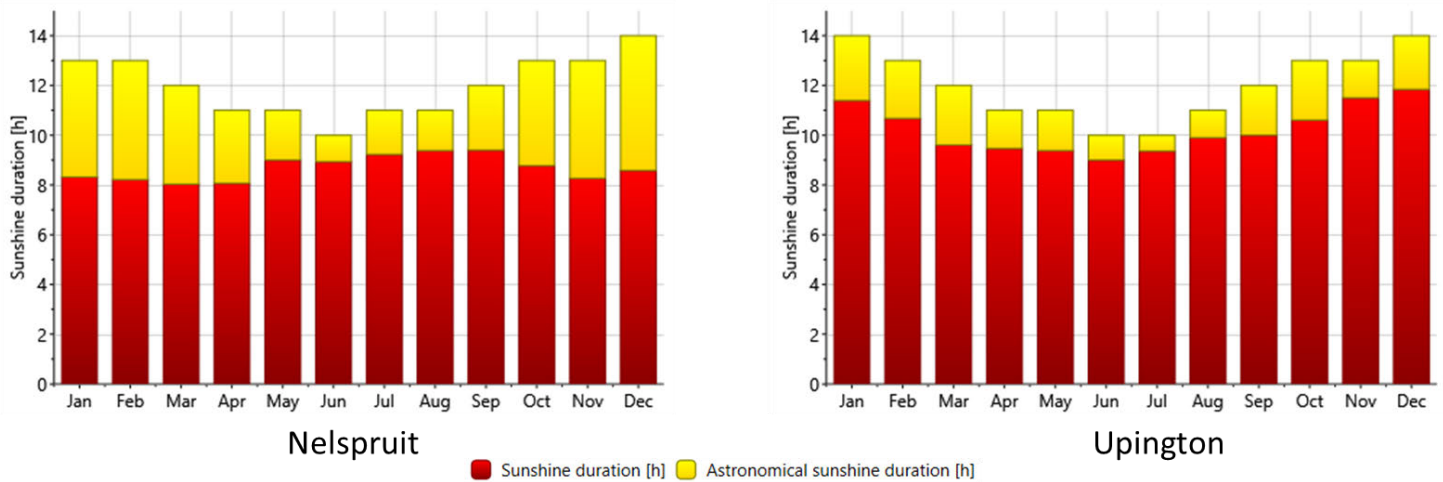
#### **Influence of geographical location and climate on BIPV's energy performance**

The above findings showed that energy production via BIPV technology for office buildings was much higher in Upington than in Nelspruit virtually in all considered cases. This implies that spatial location and climate significantly influence the energy efficiency of BIPV systems because they could control the amount and intensity of incident solar energy that is available, alongside the ambient temperature and weather, which affect the efficiency of the BIPV modules. Oftentimes, the energy production of BIPV systems is directly influenced by the quantity of solar radiation that a certain location receives. For instance, the results show that the amount of direct normal solar irradiance per year is around 2500 kWh/m<sup>2</sup> in Nelspruit and over 3000 kWh/m<sup>2</sup> in Upington, both surpassing the national average of 2500 kWh/m<sup>2</sup>. This agrees with the empirical study by Park *et al.* (2021) whose findings asserted that the potential for producing energy through BIPV is typically higher in areas with high solar irradiation and with less cloud cover unlike regions with frequent cloud cover and low solar irradiance. Likewise, this study's result regarding solar irradiance resonates the research by Mujabar and Chintaginjala Venkateswara (2021) whose experimental evidence revealed that the worldwide solar radiation is inversely associated with relative humidity and positively linked with the amount of sunlight. Generally, given Upington and Nelspruit's arid and hot climate respectively alongside the abundance of solar radiation available in the two territories, renewable energy systems can play a substantial role in this respect. This suggests that BIPV technology would be effective if applicably adopted by domestic buildings in any of the two studied locations.

Moreover, the study's findings also revealed the impact of daylight durations on energy generation of BIPV technologies in both studied climes. It was discovered that the amount of energy the BIPV systems can produce all over the day increases with the length of daylight. Even though these studied locations are not closer to the equator, yet the results shown in Figure 6.10 implies that longer daylight hours and with clear sky constitute positive factors that led to greater renewable energy potential and improved BIPV performance in these two regions. Sunshine hours can reach 9 hours in Nelspruit and over 11 hours in Upington (highest in South Africa), providing avenues for BIPV systems to attain their maximum power generation capabilities. This can be helpful in being able to satisfy building's energy needs and even supply any extra energy back to the South Africa's energy grid. This affirms

the earlier scholarly findings by Bakmohammadi and Noorzai (2022) and Taşer, Koyunbaba and Kazanasmaz (2023) who inferred that substantial daylight periods are vital to optimize BIPV energy production during times of higher demand by buildings, thereby lessening dependency on the country’s grid, and lowering costs associated with electricity. From an ecological outlook, the greater energy produced by BIPV systems during extended daylight periods if deployed to these regions can also help to combat the greenhouse gas emissions that oftentimes occur from traditional energy supply to usual buildings.

**Figure 6.10:** Results for sunshine periods in Nelspruit and Upington



Meanwhile, some slight contrasts in this study in relation to some previous research towards BIPV’s optimal energy performance in the two studied localities may be evident in geographical and climatic factors such as distance to equator, temperature, and prevailing wind. These two South African cities are in the Southern hemisphere and situated at relatively far distances from the equator. Some extant studies by Jakica *et al.* (2019) and Berger *et al.* (2019) alluded that world regions with higher latitudes (like South Africa) farther from the equator may experience drawbacks in energy generated by BIPV systems. Nonetheless, this does not affect the viability of their ultimate energy production in Nelspruit and Upington. It is noteworthy that BIPV systems can still achieve high capacity utilization factors in South Africa when they are correctly built and installed in line with national standards (Ziuku and Meyer 2013). Thus, the optimal power output by the green technology of BIPV systems can be attained in Nelspruit and Upington. With respect to temperature, it was reported that the fourth hottest temperature in South Africa’s record occurred within Upington at 41.7°C in 2022 (SAWS 2022). Consequently, findings from extant research surmised that regions with intense heat may see reduced total energy output produced through BIPV technology when compared to places with moderate temperatures (Domjan *et al.* 2020; Kant *et al.* 2020). However, based on site selection matrix for a planned BIPV project, Upington was considered to offer some of the finest sun irradiation in South Africa and the globe (Colloty 2020). Interestingly, a direct correlation usually exists between solar

radiation and temperature gain. This demonstrates that a synergistic structure and potential to strongly deploy BIPV technology is possible in Upington. Also, previous surveys reported that one of Africa's earliest concentrated solar PV power plants is sited near this region where it produces 50 MW of energy via over 4000 solar mirror panels (One' 2023). This same scenario could typically apply to Nelspruit having marginal temperature difference from Upington. In the meantime, considering the prospective higher temperatures through climate change in upcoming years, promising solutions such as BIPV thermal systems and BIPV-radiative cooling systems can be introduced to compliment BIPV technology.

### **Influence of orientation and inclination angles on BIPV's energy performance**

The study analysis was also dependent on the BIPV tilt angle, orientation angle and the selected cities while the findings unveiled the essence and impact of these factors on energy performance. It was observed from the results above that the lowest energy outputs were recorded in higher inclination angles (like 30°). However, under lower tilt angles (such as 20°), the BIPV modules generated the utmost energy output for residential buildings in both regions. This suggests that the designed layout made it possible to install more BIPV modules because a smaller distance is needed between them. Similarly, the lower angles increased the overall electricity production for residential buildings and consequently, more energy output per kilowatt peak could be generated. This scenario is vice versa whenever inclination angles are higher, though they might be the optimum tilt angles for the specific locations. The narrative from this study's findings agrees with previous research by Asfour (2018) whose results concluded that lower inclination angles like 20° are imperative if the aim is to optimize both power generation and energy savings in buildings.

Also, the study's findings indicated the impact of orientation angles on energy performance of BIPV in all cases as both north and east-west directions were considered. It was observed that north facing BIPV systems produced lesser energy output when compared to east-west orientations. As mentioned earlier, the east-west split outperforms northward orientations at very significant rates of about 48% (see Table 6.2) although some scholars recommended northward direction for BIPV systems located in Southern Hemisphere regions like South Africa (Zomer *et al.* 2013; Cibi and Manikandan 2021). This is primarily because BIPV systems oriented in the east-west direction have a dual contextual advantage of harnessing more sunlight from morning to late afternoon hours which could favourably help to meet the energy demand profiles from building occupants in Nelspruit and Upington all over the day. Interestingly, the study's analysis and findings in this context aligns with extant empirical studies like Yadav, Panda and Hachem-Vermette (2020) and Abu Qadourah (2022) whose findings inferred that positioning BIPV systems along the east-west orientations is beneficial as they produce more consistent output of power throughout the day, thereby optimising own-use energy with self-

sufficiency. Likewise, BIPV modules arranged in east-to-west direction require shorter row layout to reduce shading, which results in additional installation space and capacity.

This implies that BIPV systems' orientation and tilt angles play a significant role on the quantity and quality of solar irradiance that touches their PV modules, consequently impacting how efficient they are at producing renewable and ecofriendly energy for buildings. This is entirely evident in the present energy supplied as well as the envisaged lifecycle of BIPV systems soon. It is worth mentioning that considering the adjustable inclination angles (20°, 26° and 30°) in this study, the energy efficiency of these ecological solutions can be optimized under varying weathers or seasons. On this wise, the energy generation can be maximized via these BIPV systems for domestic users all through the year. Albeit this can incur extra maintenance cost during the lifespan of the BIPV systems as opined by some scholars (Wang, Cheng and Yang 2020; Vandewetering, Hayibo and Pearce 2022). Thus, positioning the BIPV modules at optimally fixed inclination angles could be an alternative and beneficial solution (Tripathy *et al.* 2017). The major challenge in this regard is deciding the ideal and ultimate angle that can provide the highest energy to be generated for buildings. For instance, a numerical study by Asfour (2018) employed the EnergyPlus simulation approach to determine the most suitable fixed tilt angle after many iterations of different angles. The findings showed that a fixed tilt angle of 30° is the best location for BIPV installation to maximize electricity output.

In the meantime, it is crucial to consider additional elements including the regional climate, a shading analysis, and the unique energy needs of the BIPV systems as these factors are closely interdependent alongside the orientation and inclination angles. The BIPV systems can capture the most irradiance (a vital climatic factor) possible during the day if they are properly aligned with the sun's path (for orientation angles), increasing system efficiency and energy output. Overall, it could be inferred that BIPV system orientation and inclination angles significantly affect their energy efficiency in the study locations, although from a global perspective, a single, universal ideal angles may be challenging to implement for all cases.

#### **6.4 Chapter Summary**

This chapter investigated the energy-saving potential and applicability of BIPVs systems. The study used the case studies of Nelspruit and Upington to pragmatically analyze the adoption of green BIPV systems in the hot interior and arid interior climate zones of South Africa. Results showed that Upington had greater generated energy and power output by the BIPV modules than Nelspruit in all case scenarios taken into consideration.

# CHAPTER 7

## Conclusions and Recommendations

### 7.1 Chapter Overview

In order to fulfil the study's aim, the earlier chapters gave an outline of the study and afterwards utilized a variety of research approaches that answers the research objectives. Thus, the current chapter draws a conclusion by outlining the research's aims and objectives alongside their findings. Moreover, the study's significance, value, theoretical and practical contributions were affirmed. Finally, the study's limitations were highlighted while providing pertinent recommendations for future research.

### 7.2 Review of Research Objectives and Conclusions

This research vigour was achieved via some stated objectives that are relevant to the study's aim. The current study examined the crucial and multifaceted field of energy-efficient green buildings. The research sought to make a significant contribution to the larger objective of sustainable development and the construction of a greener and more formidable built environment via extensive literature surveys, quantitative research methods, and real-world case studies. Also, the study unmistakably demonstrated the essence of energy-efficient green structures in tackling ecological problems, lowering carbon emissions, and preserving priceless natural resources. It highlighted the value of legislative and regulatory policies by governments, regional and international bodies to promote its global adoption and national acceptance especially in South Africa, while offering certifications and incentives as rewards. Additionally, the study uncovered and discussed the trending innovative digital technologies regarding the subject matter. From blockchain technology and internet of things to artificial intelligence, these technologies were discovered to improve the overall sustainability of green buildings from a lifecycle perspective. Similarly, a variety of classical, metaheuristic and data-driven optimization approaches that can improve energy-efficient green buildings were explored. These acted as complementary and potent techniques to tackle the complexities of green buildings as modern technologies keeps evolving.

By developing energy-efficient models for green building optimization, this research aimed to provide ways to improve buildings' energy efficiency and reduce their energy use and carbon emissions while operating in various climates and proffer positive impacts on South Africa's built environment. Figure 7.1 illustrates an empirical framework to assert the findings that emanate from this research.

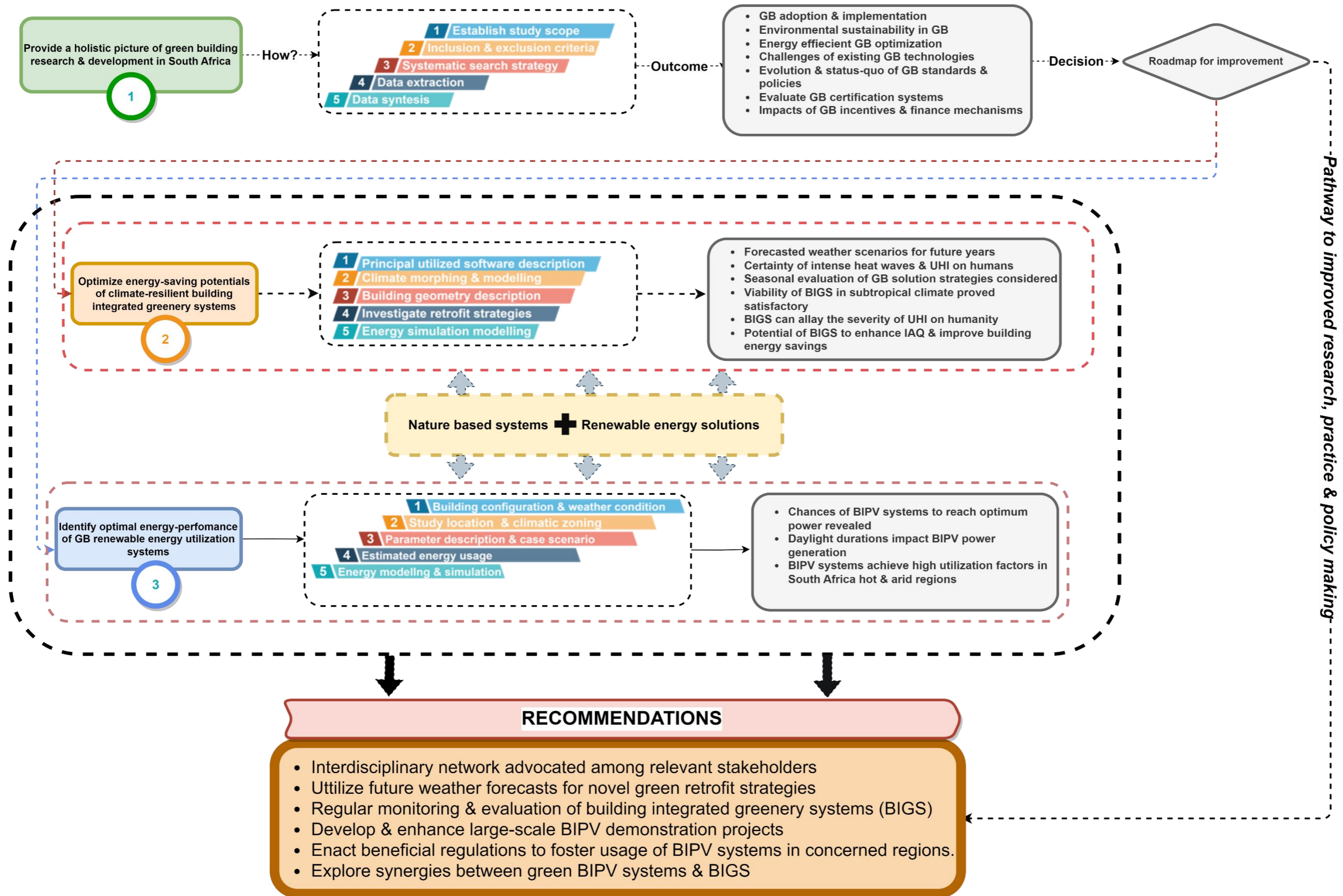


Figure 7.1: Framework for implementation strategy

To fulfil the purpose of the study, three main research objectives were defined and followed namely:

- 1 To provide an overview on status-quo of green building development in South Africa with a view to explore the status quo and provide roadmap for improvement.
- 2 To examine the energy-saving potential of incorporating building-integrated greenery systems towards climate-resilience in the subtropical climate zone of South Africa.
- 3 To investigate the energy-performance of green building renewable energy utilization systems within South Africa's hot and arid climate zones.

A variety of research methods were utilized to accomplish the aforesaid objectives which are outlined explicitly in Chapters 4 to 6. Additionally, the major findings were duly analysed and discussed while specific implications and conclusions pertinent to each objective were provided in these chapters. Thus, the key findings and conclusions are surmised below.

### ***7.2.1 To provide an overview on status-quo of green building development in South Africa with a view to explore the status quo and provide roadmap for improvement.***

To offer a clear picture of the trend and trajectory of green building issue in South Africa, this objective explored a scoping overview and content synthesis of 33 scholarly works with the aim of improving decision and policy making on the subject matter. The study mapped and reported the major features of green building in South Africa's construction sector.

Findings revealed that although the nation has myriad of famous green construction developments, scientific research advances have not really taken off to full expectation, compared to foreign climes. Most works advocated for green building adoption and implementation which were also complemented through standards, certification systems and financial incentives in South Africa domain. However, in specifics, matters regarding optimised energy performance and post-occupancy evaluation of existing buildings were underexplored. Moreover, although South African building industry professionals are highly aware of green building technologies, the usage has not increased as anticipated.

The study affirmably inferred the necessity of interdisciplinary research, utilizing cutting-edge digital technologies all over the lifecycle of sustainable construction, and the need for prominent practitioners to investigate more of the key success elements. Wrapping up, the study concluded that an approach to obtaining buildings that are energy-efficient can be made possible by deploying sustainable building prototype models in the local setting.

### ***7.2.2 To examine the energy-saving potential of incorporating building-integrated greenery systems towards climate-resilience in the subtropical climate zone of South Africa.***

To counteract the dire menace of global warming on humans and built environment, this research study objectively explored the feasibility of three greenery measures and their optimal energy-saving capacities in Durban's subtropical climate zone. Forecasted weather for years 2030, 2050, and 2080, alongside three energy demand rise mitigation techniques, (green roof, green walls, and thermally insulated green envelope materials), were considerably developed in a university building as a reference study using a parametric simulation method.

The study's findings revealed that extreme heat waves would occur more frequently at higher peak temperatures in the future years while the annual rate of building energy use in the study area will surge by 8-24% between 2030 and 2080. It was discovered that a large portion of heat gains are driven by thermal transfer via the envelope instead of incident solar radiation, based on a sub-hourly evaluation of thermal transmission rates and building energy demand over a summer design day and a winter design day. Meanwhile, the study found out that these greenery systems can greatly assist in achieving the lofty objective of green building and a sustainable urban environment throughout these anticipated seasons. The methods for adapting to climate change were successful via these nature-based solutions as opposed to orthodox buildings with no retrofit plan. Compared to installing green walls and green roofs, the study's findings revealed that including thermally-sound green construction elements to the building envelopes served as the most superior option since it outperforms the former duo in terms of adaptability, resilience, and energy saving. On the whole, the study results underscored the positive impacts of these responsive measures to combat climate change. Based on the findings, the following conclusions were drawn.

- 1 These nature-based solutions demonstrated some satisfactory energy-saving potentials, thereby reducing over-reliance on fossil fuel energy by building occupants.
- 2 Evidently, the key to enhancing energy-saving benefits of these systems was to optimize design parameters including plant selection, greenery covering, double-glazing, extruded polystyrene and overall system integration.
- 3 These systems serve as natural insulators, moderating inside temperatures, lowering cooling and heating loads, and decreasing over-reliance on mechanical systems that consumes fossil fuels.
- 4 Implementing these building-integrated greenery systems in densely populated urban locations like Durban could lessen the harmful effects of urban heat islands and improve air quality within buildings.
- 5 Overall, the study concluded that these greenery and thermally-sound systems can be carefully

used to create a synergistic impact that will boost building resilience, reduce carbon emissions, and increase energy efficiency under current and prospective climate change.

### ***7.2.3 To investigate the energy-performance of green building renewable energy utilization systems within South Africa's hot and arid climate zones***

In light of the growing challenges caused by climate change and resource scarcity in some climates within South Africa, the study pragmatically examined the incorporation of building-integrated photovoltaics (BIPV) systems in the hot interior and arid interior climate zones of the country. Specifically, these renewable energy sources were typically studied on hypothetically modelled office building using Nelspruit and Upington as reference points. The analysis established the operational energy performance of these systems by considering various aspects such as tilt angles, installation capacity, azimuth angles, solar irradiance, daylight factor, among others.

The findings showed that the studied regions are marked with high degree of global horizontal irradiance, thus creating an avenue for deployment of renewable energy technologies. It highlighted the importance of creating BIPV systems that can withstand high temperatures while still generating energy in varying capacities. In all considered case scenarios, the generated energy and power output by the BIPV modules were found higher in Upington than Nelspruit, affirming the assertion that the amount of solar radiation that a specific place receives frequently has a direct impact on how much energy BIPV systems produce. Moreover, the findings revealed that there are opportunities for BIPV systems to reach their optimum power generating potential because sunshine hours can approach 9 hours in Nelspruit and over 11 hours in Upington (the highest in South Africa). Furthermore, as both north and east-west directions were taken into consideration, the data showed that orientation angles had an effect on BIPV's energy performance in all circumstances. When compared to east-west orientations, BIPV systems with a northward facing were shown to yield less energy. Similarly, it was also revealed that higher inclination angles generated lower energy outputs, while lower tilt angles produced the highest energy output for domestic buildings in both locations from the BIPV modules.

Consequently, the following conclusions were arrived at based on the findings:

- 1 Areas such as Nelspruit and specifically, Upington with high solar radiation and little cloud cover often have more potential for producing energy using BIPV.
- 2 This renewable energy strategy can maximize occupant comfort and wellbeing while ensuring optimum energy efficiency and ecological performance.
- 3 Geographical location, climate, orientation angle, tilt angle, and installed BIPV system capacity constitutes the major factors that influence its energy performance in the two study locations.

- 4 The improved BIPV systems can alleviate over-dependence on conventional energy supply for buildings in such regions, while achieving greater energy conversion efficiency.
- 5 To sum up, in South Africa's hot and arid regions, improved BIPV systems can produce clean power for building energy performance while helping with energy conservation, climate change mitigation and assist the country in keeping its climate-related international commitments.

### **7.3 Significance and Contribution of the Study with Recommendations**

This research study adds to the knowledge corpus and practice by highlighting salient approaches for optimizing green building energy efficiency that can foster a resilient and sustainable built environment. Specifically, the significance of the scoping study hinges on its input to advancing the state of knowledge regarding South African green building research and development. The study offers a platform for well-informed decision-making, policy development, and focused research efforts in the field of sustainable building by methodically charting extant studies, finding research gaps, and providing future roadmaps. Thus, researchers and academics can identify understudied topics and potential areas for additional study via salient excerpts from the study. It promotes cooperation and information exchange between academic institutions. Moreover, it can aid professionals in making wise judgments and enhance the environmental impact of their projects in a positive manner.

On the basis of the scoping review's study, the following recommendations are inferred to advance South African green building research and practice:

- 1 To effectively handle the complex issues surrounding green building, interdisciplinary network is advocated among researchers, architects, engineers, social scientists, and policymakers.
- 2 Promising research results can be translated to efficient laws and rules that aid green building development.
- 3 To ascertain that solutions are in line with their requirements, preferences, and cultural setting, local communities and municipalities should be engaged with green building-led initiatives.

The relevance of the study on greenery-based systems for green building lies in its contribution to energy efficiency and sustainable building techniques. Specifically, the knowledge from this study can be duly explored by architects, construction professionals, and allied experts to design energy-efficient structures that are sensitive to the climate in Durban and beyond. Similarly, building owners and managers can utilise this information to assist decisions about putting green features into new development or remodeling existing facilities. Since the study offers beneficial energy-saving and ecological effects, it adds to the knowledge body on green building practice. Thus, this information can be used by environmental organizations to promote further adoption of green construction regulations via

municipality-led initiatives.

Consequently, the suggestions below were made in light of this study's findings and significance:

- 1 Future meteorological forecasts should be utilized to devise cutting-edge green retrofit strategies and novel ecofriendly materials to lessen upcoming harsh situations from heatwaves on humans.
- 2 The merits of building-integrated greenery systems and their contribution to energy efficiency and sustainable urban development should be made known to the public.
- 3 Building-integrated greenery systems should be regularly monitored and evaluated in order to determine their effectiveness in reducing energy use and pinpoint potential improvement areas.
- 4 To encourage the broad deployment of building-integrated greenery systems in both modern and existing buildings, incentive programs and financial support should be implemented.

The importance of the study of BIPV technology rests in its advancement of environmentally friendly energy options for buildings in South Africa's hot and arid regions. It offers pragmatic principles that can aid urban planners and policymakers to incorporate this eco-friendly technology into designs of new and existing buildings, thus promoting sustainable urban growth and lowering cities' carbon footprints. Also, integrating the BIPV technology can help to reduce the peak demand for energy by residential building users particularly during the hotter months, thus reducing load on the energy grid and improving grid stability. Moreover, the study on BIPV in hot and arid climates of Nelspruit and Upington also adds to the knowledge corpus in the spectrum of green building and renewable energy integration. This can be a useful reference that offers lessons and outlooks for other regions dealing with comparable climatic issues, both in South Africa and beyond.

Going forward, the following recommendations can be made in order to develop the field:

- 1 To illustrate the efficacy and merits of these systems to the public and industry stakeholders, large-scale BIPV demonstration projects should be developed and enhanced in South Africa's hot and arid regions.
- 2 It is recommended that all practitioners involved in green building design and BIPV system invest in educational programs and workshops to improve their skills and knowledge.
- 3 The enactment of beneficial regulations, including feed-in tariffs and tax incentives should be promoted to foster the use of BIPV systems and ecologically friendly construction techniques.

#### **7.4 Study's Limitations and Recommendations for Future Research**

While the first objective of this study was achieved via a scoping review approach to unveil the status of green building research in South Africa, it has its own limitations. First off, only certain keywords

inside the spectrum of green building were investigated because it was fairly impractical to explore every single keyword during the search procedure. Similarly, the study only included information from three academic repositories and excluded information from additional sources, like technical articles and other grey literatures. Moreover, majority of the articles meeting the eligibility criteria did not have their worth assessed, being a scoping review. Meanwhile, the justification for using this approach was demystified in Chapter 4. Thus, as innovative research trends are emerging in the field of sustainable construction, prospective studies can explore budding terms within green building terrain to have a modern grasp of the subject with practical implications.

In achieving the second and third objectives, some parametric simulation methods were employed, while findings were validated using some established validation metrics alongside comparison with extant relevant studies. Experiments or field trials to evaluate the energy-saving performance measures were not explored owing to backdrop in utilizing ideal testing facilities. Moreover, this study focused largely on institutional and residential/office buildings and not fully delve into how it applies to other building typologies. Furthermore, only three South African climatic regions (hot interior, arid interior and subtropical coastal zones) were considered, thus generalization of the research upshots may largely apply to these locations. Similarly, the study mainly concentrated on energy performance and ecological impacts while financial feasibility study is not really examined, which may create likely concerns on their long-term cost-benefits.

In view of the above, further research is needed in the following areas:

- 1 New studies can delve into holistic systematic and critical reviews, and survey pragmatic green building projects for comparative analysis.
- 2 Prospective research can explore an ideally combined simulation and experimental testbeds when gathering and validating results of building energy simulation models.
- 3 Future studies can investigate the potential of nature-based greenery solutions for other existing and new building typologies.
- 4 Future research might examine the effects of additional electrical components on buildings and BIPV modules.
- 5 Future studies should investigate practical measures that can reduce the likely overheating and fire risk of BIPV modules.
- 6 Scholars can explore the synergies between green building-integrated photovoltaic systems and building-integrated greenery systems to evaluate their mutual benefits and economic viability.
- 7 Researchers can conduct studies on the lifecycle design optimization of green building envelopes in various climatic regions of South Africa using data-driven approaches.

## **7.5 Chapter Summary**

The primary findings and conclusions of this study are discussed in this chapter. Likewise, the study's significance, contributions, and limitations were described. Lastly, recommendations for prospective research were proffered.

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# APPENDIX

## Appendix A

### Qualitative Synthesis/Content analysis of included articles

Author(s)	Province	Title	Scope of study	Focal point(s)	Core finding(s) & result(s)	Recommendations
Mistry and Spocter (2022)	Western Cape	Exploring the “eco-ness” of South Africa’s eco-estates	Eco-estate; eco-practices; gated communities; green buildings; sustainable development	<ul style="list-style-type: none"> <li>● Examination of the eco-friendliness of eco-estates.</li> <li>● Evaluated how much eco-living is practiced in various lifestyle estates</li> </ul>	<ul style="list-style-type: none"> <li>● Eco-practices in the management of solid waste, water, and energy are laudable.</li> <li>● It is debatable if land and land-use practices have any positive effects on maintaining the societal sustainability, despite being advantageous for environmental sustainability.</li> <li>● Eco-practices are not strictly regulated or required for estate inhabitants.</li> </ul>	<ul style="list-style-type: none"> <li>● National regulations should be developed to regulate eco-practices in estates to achieve their marketing demands of residential living in tune with nature.</li> </ul>
Dlamini and Yessoufou (2022)	Gauteng	Residents and professionals’ perspectives on energy and water consumption while transiting from conventional to sustainable housings in South Africa	Sustainable construction; construction industry; awareness; residents’ satisfaction-level; developers	<ul style="list-style-type: none"> <li>● Assessment of the degree to which professionals are aware of the concept of sustainable construction.</li> <li>● Appraisal on residents’ awareness level and feedback on sustainable actions utilized.</li> <li>● Evaluation on perceived barriers, prospects, and remedies for promoting inclusive sustainable construction in SA.</li> <li>● Discovered what factors led to the adoption of sustainable water-saving strategies</li> </ul>	<ul style="list-style-type: none"> <li>● Vague knowledge of ‘green construction’ concepts alongside its huge investment costs are the major barriers within the region</li> <li>● Implemented energy-saving strategies considerably reduces energy use in a GB estate than non GBs</li> <li>● Residents are aware of the GB initiative and projects within their locality</li> </ul>	<ul style="list-style-type: none"> <li>● Raising AEC professionals' awareness of the Building Act.</li> <li>● Financing green construction and educating relevant AEC stakeholders on how GB can help alleviate global warming.</li> <li>● Creating organizations tasked with educating the construction sector about environmental and sustainability concepts</li> </ul>
Windapo <i>et al.</i> (2021)	Western Cape	Use and performance of conventional and sustainable building technologies in low-income housing	Conventional building technologies; Low-income housing construction Reconstruction & development programme low-income houses Sustainability performance	<ul style="list-style-type: none"> <li>● An investigation on the application of sustainable building techniques in the construction of affordable housing in SA</li> </ul>	<ul style="list-style-type: none"> <li>● Traditional building components have a substantially lower level of sustainability due to the extensive usage of concrete.</li> <li>● Innovative building materials emit less carbon dioxide during manufacturing, which reduces their environmental impact.</li> </ul>	<ul style="list-style-type: none"> <li>● Clients in the public sector who provide low-income housing should promote the use of GB techniques.</li> <li>● The GBCSA should adopt policies that explicitly target low-income housing development in order to assess the socioeconomic viability and environmental impact of the houses built.</li> </ul>
Sinxadi and Awuzie (2021)	Free State	Eliciting project managers' perceptions regarding economic sustainability incorporation on construction projects: A Bloemfontein case study	Construction industry, Economic sustainability, Sustainable construction, Project managers	<ul style="list-style-type: none"> <li>● Examination on project managers' viewpoints and comprehension on how to incorporate economic sustainability into building projects</li> <li>● To determine the factors inhibiting the prioritization of economic sustainability considerations in order to achieve acceptable trade-offs.</li> </ul>	<ul style="list-style-type: none"> <li>● Project managers lacked the knowledge of how to inspire for the precedence of economic sustainability in green construction in comparison with environmental and social dimensions.</li> </ul>	<ul style="list-style-type: none"> <li>● The inclusion of sustainability considerations in infrastructure projects</li> </ul>
Owoha <i>et al.</i> (2021)	Western Cape	Categorising green building features in developing countries: The case of South Africa	Sustainability, Developing countries, Green building features	<ul style="list-style-type: none"> <li>● An investigation to the GB idea by developing a useful framework for classifying features of GB</li> </ul>	<ul style="list-style-type: none"> <li>● Kitchen and bathroom fixtures with water-saving technology, a megawatt solar power facility, and water metering are the top three most crucial GB features based on mean rank</li> <li>● Further underlying grouped features were discovered through exploratory factor analysis.</li> </ul>	<ul style="list-style-type: none"> <li>● Design and construction firms establish a framework for valuing green buildings based on additional features and functionality.</li> <li>● Imminent research should emphasize the significance of developing better approach to implementing effective valuation techniques and identifying other appropriate methods for the purpose of GB features.</li> </ul>
Marsh, Brent and de Kock (2021)	Western Cape	Understanding the barriers and drivers of sustainable construction adoption and implementation in South Africa: A quantitative study	Sustainable construction, Barriers, Drivers	<ul style="list-style-type: none"> <li>● Identified how AEC industry stakeholders used the Capability, Opportunity, Motivation-Behaviour model and Theoretical Domains Framework to identify the barriers to and drivers of green construction practices.</li> </ul>	<ul style="list-style-type: none"> <li>● Greater public understanding, motivation, and need for sustainable building practices will speed up their implementation</li> </ul>	<ul style="list-style-type: none"> <li>● The access to education, training, and upskilling for stakeholders should be provided by organizations.</li> </ul>

		using the Theoretical Domains Framework and COM-B Model			<ul style="list-style-type: none"> <li>● The huge investment cost of GB and perceptions of the social and economic benefits of sustainable construction were highlighted as the main obstacles.</li> </ul>	<ul style="list-style-type: none"> <li>● Government should create and regulate the laws and policies that govern the implementation and use of SC.</li> <li>● To encourage sustainable growth in the built environment, universities must incorporate sustainability into their teaching and research.</li> <li>● There is an urgent need for local life cycle assessment-based research on the environmental impacts of various construction products and processes in SA and allied emerging economies</li> </ul>
Crafford, Wessels and Blumentritt (2021)	Western Cape	Sustainability and wood constructions: a review of green building rating systems and life-cycle assessment methods from a South African and developing world perspective	Wood; green building; rating systems; life cycle assessment; developing world	<ul style="list-style-type: none"> <li>● An examination on existing GB rating systems, with a particular emphasis on the assessment of wood and wood-based materials</li> <li>● To find out research that compared wood-based constructions to alternate solution building products via life-cycle assessment</li> <li>● To apply the observations to specific opportunities and challenges in the context of emerging economies such as SA</li> </ul>	<ul style="list-style-type: none"> <li>● A building's embodied energy is far smaller than its running energy, according to previous studies on life-cycle assessment</li> </ul>	
Watkins and Sunjka (2020)	Gauteng	Combining green building and lean construction to achieve more sustainable development in South Africa	Green building, lean construction, sustainable development	<ul style="list-style-type: none"> <li>● To provide clear understanding of the nexus between lean construction and GB that exist at every phase of a construction development project.</li> </ul>	<ul style="list-style-type: none"> <li>● GB and lean construction principles, processes, tools, and technologies may be applied simultaneously throughout all phases of development and give several advantages in each</li> <li>● BIM is essential for supporting and promoting green building and lean construction</li> </ul>	<ul style="list-style-type: none"> <li>● Further research should focus on: <ul style="list-style-type: none"> <li>● how lean construction and green building interplay during the development's deconstruction and destruction phase;</li> <li>● undertaking qualitative and quantitative research on how lean construction and green building interact in the supply chain; adoption of GB and lean construction in each project phase within SA</li> </ul> </li> </ul>
Simpeh <i>et al.</i> (2020)	Eastern Cape	Analytical taxonomy of challenges to the implementation of green building projects in South Africa	Built environment professionals; categorisation system; challenges; developing country; Green building	<ul style="list-style-type: none"> <li>● An assessment of the key barriers to the implementation of GB projects in South Africa.</li> </ul>	<ul style="list-style-type: none"> <li>● The primary barriers to implementing green construction projects are higher initial expenses, prices related to green technologies and materials, and GB certifications.</li> <li>● Further underlying grouped features were discovered through exploratory factor analysis</li> <li>● A financial reward was the best indicator of how likely people were to adopt GB, followed by socio-environmental benefits.</li> </ul>	<ul style="list-style-type: none"> <li>● To obtain a competitive edge over conventional construction methods, GB must identify obstacles and take proactive measures to address them.</li> <li>● SA government should employ GB and provide incentives to</li> </ul>
Simpeh and Smallwood (2020)	Western Cape	An integrated model for predicting the probability of adoption of green building in South Africa	Attribute of adopters, Benefits, Economic enablers, Green building, Social influence, South Africa	<ul style="list-style-type: none"> <li>● To explore the anticipated impact of the economic and non-economic elements thought in motivating stakeholders to embrace GB practices.</li> </ul>		
Marsh, Brent and de Kock (2020)	Western Cape	An integrative review of the potential barriers to and drivers of adopting and implementing sustainable construction (SC) in South Africa	Sustainable construction; Drivers; Barriers; Review	<ul style="list-style-type: none"> <li>● An investigation to find out the most substantial barriers to and drivers of green construction adoption and implementation</li> </ul>	<ul style="list-style-type: none"> <li>● Major barriers to adopting and implementing SC are a lack of awareness of SC, resistance to changing conventional building processes, a dearth of building codes and regulations, a lack of incentives and incentives, and a limited availability of green product suppliers, materials, and technologies.</li> </ul>	<ul style="list-style-type: none"> <li>● Further research could examine the results of studies on the factors that drive and hinder SC from the viewpoints of the same or different stakeholder groups.</li> </ul>
Hoffman <i>et al.</i> (2020)	Gauteng	Trends in application of Green Star SA credits in South African green building	Application trends, green building, South Africa, sustainability, trends	<ul style="list-style-type: none"> <li>● To discover if there are any patterns in the credits earned by green building-certified projects, which is a crucial aspect of using the Green Star SA tool</li> </ul>	<ul style="list-style-type: none"> <li>● More than 80% of recognized projects typically complete 21 of the 67 credits.</li> <li>● The Green Star SA rating level has a positive correlation with frequently used credits and a negative correlation with seldom used credits.</li> </ul>	<ul style="list-style-type: none"> <li>● To examine the fundamental reasons of the trends found, they should be explored more closely.</li> <li>● Credits with technological difficulties, budgetary limitations, the cost to point ratio of the credits, and credits only applicable to particular project categories should all be considered.</li> </ul>

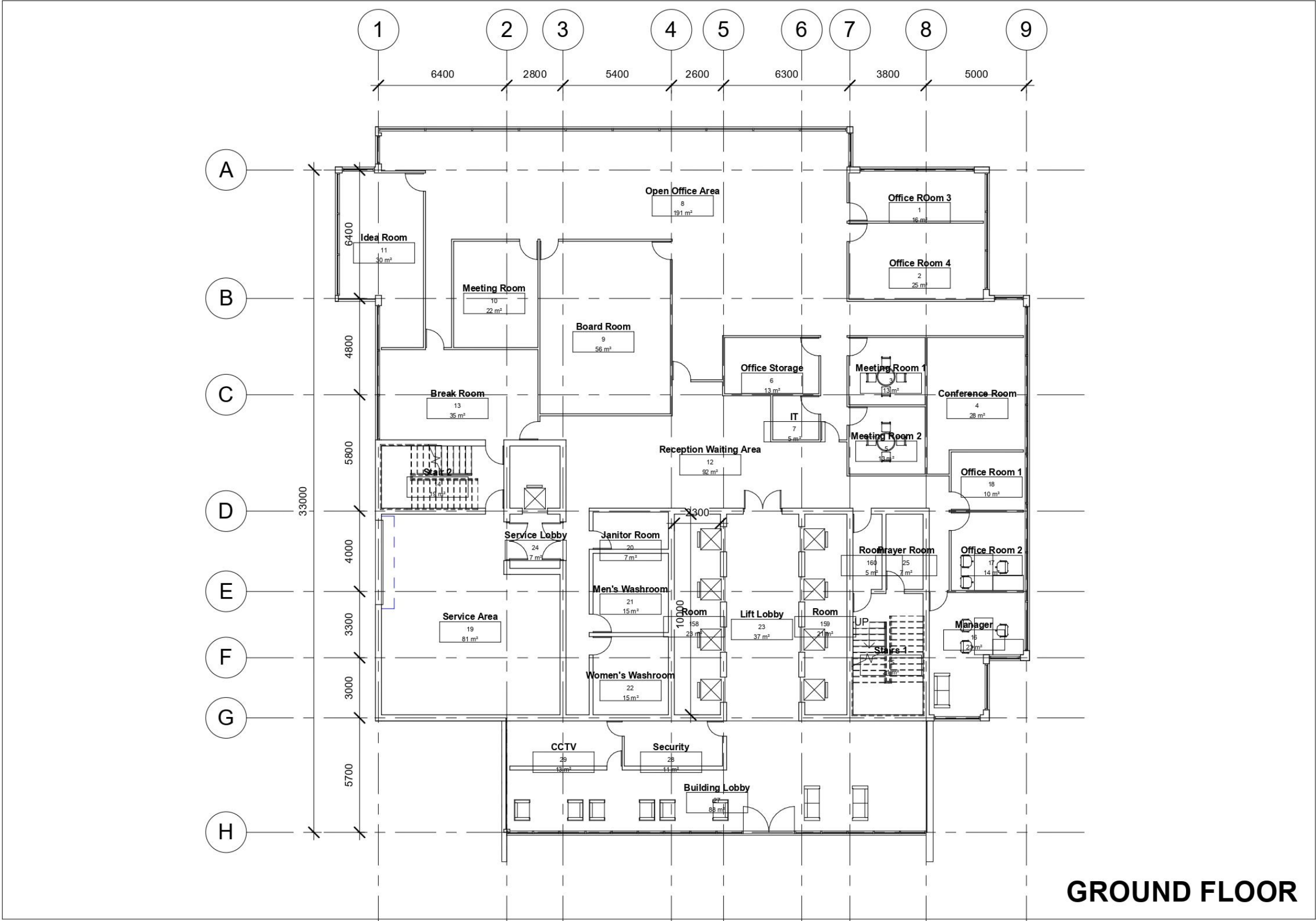
Eromobor, Das and Emuze (2020)	KwaZulu-Natal	Influence of building and indoor environmental parameters on designing energy-efficient buildings	Building envelope, Design, Efficiency, Energy consumption, Energy performance, Sustainable buildings	<ul style="list-style-type: none"> <li>● Determining how different building and indoor environmental factors affected how energy-efficient South African university buildings were.</li> </ul>	<ul style="list-style-type: none"> <li>● The building's and the inside environment's humidity, temperature, volume, illumination, and window width ratio, within this sequence, greatly influenced energy usage.</li> </ul>	<ul style="list-style-type: none"> <li>● In order to construct sustainable university buildings, the interaction between the building and indoor environmental features should be taken into account both individually and in whole, and their impact should be evaluated.</li> </ul>
Boshoff and Mey (2020)	Gauteng	The building emission reduction potential of South African residential building efficiency tools - A review	Building energy efficiency tools, climate change mitigation, green buildings, residential sector	<ul style="list-style-type: none"> <li>● Assessed the efficacy of energy-saving solutions for buildings to lower CO<sub>2</sub> emissions.</li> </ul>	<ul style="list-style-type: none"> <li>● Strong possibilities exist to reduce energy intensity of residential buildings</li> </ul>	<ul style="list-style-type: none"> <li>● To meet targeted climate obligations, it is imperative to prioritize more effective and timely required restrictions for new construction.</li> </ul>
Oguntona <i>et al.</i> (2019a)	Gauteng	Benefits and Drivers of Implementing Green Building Projects in South Africa	Construction industry, Green building, Environmental challenges, Sustainable construction, Sustainability	<ul style="list-style-type: none"> <li>● To examine green construction initiatives in South Africa' AEC sector and advance environmental sustainability.</li> </ul>	<ul style="list-style-type: none"> <li>● The topmost benefits of executing GB projects include improved indoor air quality, ecosystem protection, higher energy efficiency, improved health and well-being of inhabitants, and reduced carbon emissions.</li> <li>● The top drivers in executing GB projects are increased access to funding, a more developed market for green goods and materials, increased education and training about GB technology, the provision of financial incentives, and the cost and availability of GB materials.</li> </ul>	<ul style="list-style-type: none"> <li>● Government should establish rules and guidelines that would prepare those involved in the construction business to fully embrace green building.</li> </ul>
Aigbavbo a and Thwala (2019)	Gauteng	Performance of a green building's indoor environmental quality on building occupants in South Africa	Green building, Health implications, Indoor environmental quality, Post-occupancy evaluation	<ul style="list-style-type: none"> <li>● Determined what factors affect how satisfied GB occupants are with the IEQ components of a building and what effects a building's IEQ has on occupant health.</li> </ul>	<ul style="list-style-type: none"> <li>● The building's residents were dissatisfied with the IEQ of the GB, notably with how ineffectively it was able to prevent both natural and artificial lights.</li> <li>● There are significant health effects on the building's occupants from the IEQ, particularly with regard to the level of noise and space ventilation.</li> </ul>	<ul style="list-style-type: none"> <li>● Buildings' thermal components must be created to give occupants some level of control.</li> <li>● Future GB design and construction should consider the occupants' demand for sufficient, high-quality air circulation and, most importantly, some sense of control over the structure's ventilation.</li> </ul>
Aghimien, Aigbavbo a and Thwala (2019)	Gauteng	Microscoping the challenges of sustainable construction in developing countries	Sustainability, Sustainable construction, South Africa	<ul style="list-style-type: none"> <li>● To convey the findings of an evaluation of the challenges with SC in developing nations</li> </ul>	<ul style="list-style-type: none"> <li>● The professionals that were assessed were quite knowledgeable about SC and actively involved in its application.</li> <li>● Masonry construction and surface finishing are the two areas where SC materials are most frequently used.</li> <li>● Some of the main problems are reluctance to change, client preferences, concern of rising investment costs, and a lack of information and comprehension of the notion of sustainability.</li> </ul>	<ul style="list-style-type: none"> <li>● Through the development of policies and the supply of tools for their enforcement, the government must take a proactive role in promoting SC</li> <li>● It is vitally important to increase the education and training of construction industry professionals in SC principles and concepts.</li> </ul>
Ololade and Rametse (2018)	Free State	Determining factors that enable managers to implement an environmental management system for sustainable construction: A case study in Johannesburg	Construction industry, environmental management system (EMS), sustainability	<ul style="list-style-type: none"> <li>● To examine how high and elite managers of a construction company view environmental management challenges.</li> <li>● to assess the level of their organization's support for environmental management</li> </ul>	<ul style="list-style-type: none"> <li>● Age, educational attainment, and awareness and knowledge are the three factors that may have an impact on managers' attitudes and beliefs regarding environmental issues in the construction business.</li> </ul>	<ul style="list-style-type: none"> <li>● The deployment of an EMS in the construction industry will be aided by knowledge and awareness as crucial components.</li> <li>● Environmental management training should be done on a regular basis.</li> </ul>
Fan and Xia (2018)	Gauteng	Energy-efficiency building retrofit planning for green building compliance	Building retrofit; Energy performance certificate; Green building compliance; Rooftop PV system; Economic analysis	<ul style="list-style-type: none"> <li>● Proposed an optimization model to assist decision-makers in identifying the optimum mix of retrofit alternatives for buildings to achieve policy compliance in the most affordable manner.</li> </ul>	<ul style="list-style-type: none"> <li>● The model systematically calculates the best retrofit plans for an entire building.</li> <li>● The model divides the long-term investment into more appealing to investors' annual short-term instalments.</li> </ul>	<ul style="list-style-type: none"> <li>● The model is useful and significant for decision-makers since intuitive planning will result in substandard retrofit actions</li> </ul>

Dosumu and Aigbavbo a (2018)	Gauteng	Adoption of light steel (LS) for building projects in South Africa	Sustainable construction, Construction innovation, Light gauge steel	<ul style="list-style-type: none"> <li>To investigate the advantages, problems, and solutions to the problems associated with using light steel in construction projects.</li> </ul>	<ul style="list-style-type: none"> <li>Despite the advantages of light steel, few developers adopt it because they perceive it as a risk to suppliers' and contractors' companies</li> </ul>	<ul style="list-style-type: none"> <li>In order for LS to be successfully adopted for building projects in emerging economies, awareness must be raised, and it must be ensured that the overall construction cost is less than that of traditional structures.</li> </ul>
Michael, Zhang and Xia (2017)	Gauteng	An optimal model for a building retrofit with LEED standard as reference protocol	Building retrofit; Energy savings; LEED certification; Multi-objective optimization; Water savings	To maximize the points obtained under the LEED rating system, payback duration, retrofitting costs, and energy and water savings.	<ul style="list-style-type: none"> <li>The model could serve as an ideal retrofit design that maximizes the benefits of retrofit while also achieving LEED certification for green buildings.</li> <li>By using weighting criteria, it enables the decision-maker to express preferences on specific retrofit performance measures.</li> </ul>	To achieve more accurate energy savings and, consequently, energy savings threshold points, additional energy simulation tools can be added to the examination of the modified building's energy simulation.
Ganiyu, Fapohunda and Haldenwang (2017)	Western Cape	Sustainable housing financing model to reduce South Africa housing deficit	Housing finance systems, Low-income, Financing model, housing deficit, Sustainable housing	To propose efficient housing financing models that the government might use to fulfil its obligation to provide cheap, sustainable housing.	It revealed a flagrant exploitation of the housing subsidies system by South African residents who get government-funded housing.	It is essential to utilize an all-inclusive housing financing strategy that calls for a financial contribution from the recipients to give them influence over the procedure.
Crafford, Blumentritt and Wessels (2017b)	Western Cape	The potential of South African timber products to reduce the environmental impact of buildings	Lifecycle assessment, novel truss materials, green building	To examine various roof truss systems in low- and medium-income South African house designs via a condensed life-cycle assessment methodology	Timber systems have the least negative effects on the environment overall.	More local LCA data and research are required to promote and simplify direct system comparison in the local building industry and to better account for localised environmental emissions.
Sundayi, Tramontin and Loggia (2016)	KwaZulu-Natal	An investigation into the costs and benefits of green building in South Africa	Green building, cost-benefit analysis, developing country, developer perception, green building rating system.	To help remove some of these obstacles of green development and its financial implications by examining property developers' perceptions.	Findings showed that builders are beginning to understand the financial advantages of green structures and believe that they will soon become the norm.	The use of comparable cost-benefit analysis techniques on several case studies in the local context is advised for future research to derive market-wide indicators.
Solanke and Fapohunda (2016)	Western Cape	Impacts of e-commerce on construction materials procurement for sustainable construction	Construction industry, E-commerce, E-procurement, Materials procurement, Sustainable building.	To explore the use of e-commerce as a tactic for enhancing the construction sector of South Africa's materials procurement procedure.	Sustainability advantages in material procurement for sustainable building production include reduced building costs, improved environmental protection, and improved government policy implementation.	Construction experts should instruct and teach construction stakeholders on ways for acquiring electronic materials for upcoming SC projects.
Windapo and Goulding (2015)	Western Cape	Understanding the gap between green building practice and legislation requirements in South Africa	Sustainability, Green Construction, Environmental management	To study the needs of green building legislation and practices during the execution stage of a construction projects	The stakeholders in the AEC sector could not easily be identified as being dedicated to promoting a sustainable built environment.	Regulations governing GB methods must be formalized monitored for compliance during the project implementation phase.
Seeliger and Turok (2015)	Western Cape	Green-sighted but city-blind: Developer attitudes to sustainable urban transformation	Green buildings. Building conversions. Core urban areas. Spatial transformation	To examine how developers feel about the concepts of sustainable urban transformation.	Developers frequently choose brand-new green structures over renovated and redeveloped brownfield structures, which have a greater environmental impact.	To assist mitigate some risks and manage some uncertainties associated with real estate development, a precinct strategy must be used.
Coetzee and Brent (2015)	Gauteng	Perceptions of professional practitioners and property developers relating to the costs of green buildings in South Africa	Green building; Property developer, Professional practitioners	To investigate how property developers and industry professionals perceive the GB costs.	The green building certification program's "compliance" component is overly "rules-based" and fails to sufficiently recognize creative thinking.	<ul style="list-style-type: none"> <li>It is imperative to develop a continuous program to monitor the real operational costs of buildings with Green Star certification.</li> <li>The role of local government in fostering a conducive environment for sustainable development must be increased.</li> </ul>
Windapo (2014)	Western Cape	Examination of green building drivers in the South African construction industry: Economics versus ecology	Building codes; Construction; Ecology; Energy costs	To evaluate the main factors that influence green building and assess whether they have evolved over time.	<ul style="list-style-type: none"> <li>The industry's Green Star certification system, growing energy prices, competitive benefits, and legislation are the primary forces behind green building.</li> <li>The study also shows that these important factors have not altered much over time.</li> </ul>	The South African government should enact steps to assist GB design and construction, including building laws.

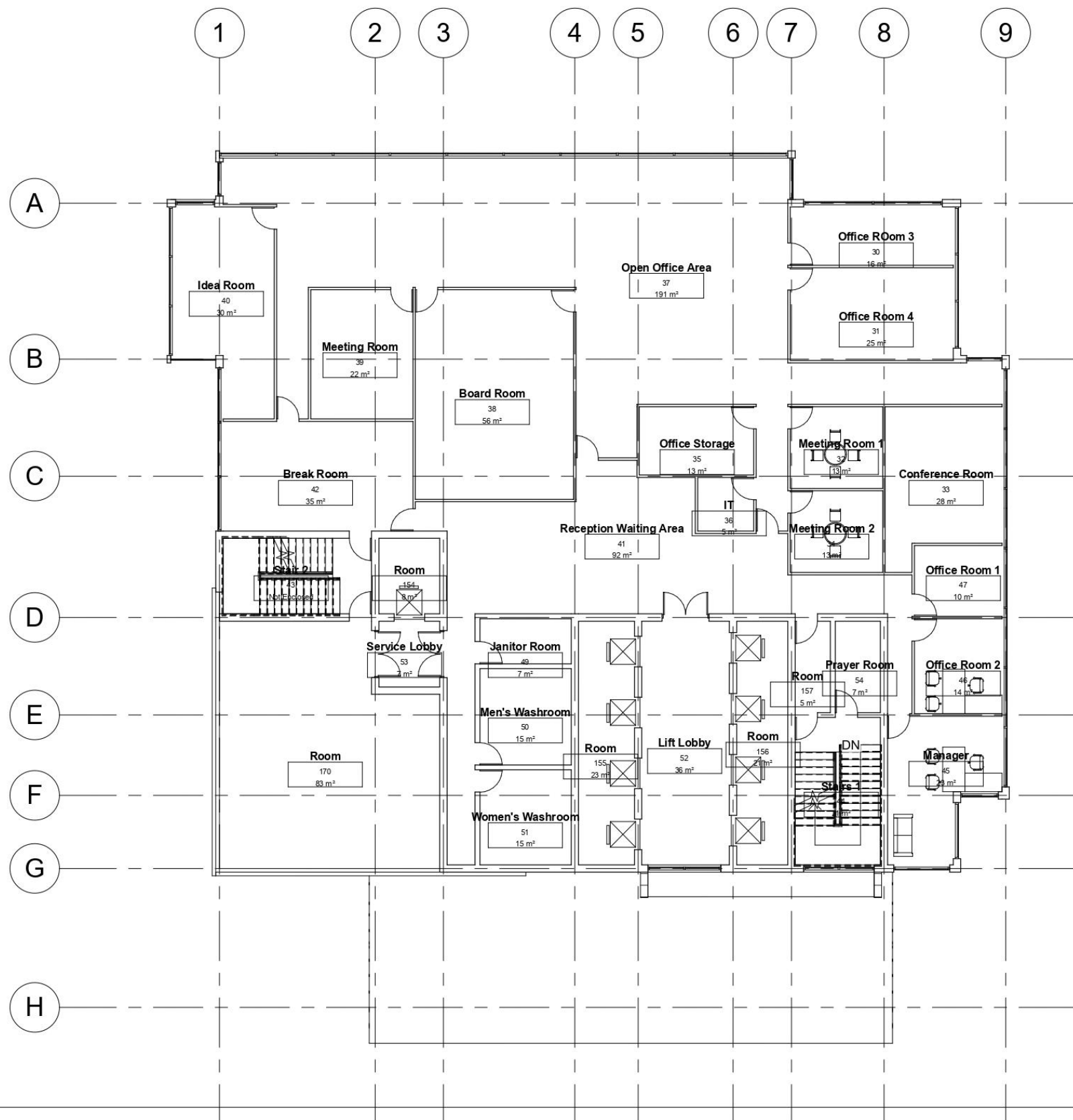
van der Bank and van der Bank (2014)	Gauteng	The regulation of renewable resources to promote energy efficiency in sustainable buildings in South Africa: A legal analysis	Environmental right, Energy efficiency, renewable resources, Sustainable development Green building.	To investigate how environmental and local government legislation governing the use of renewable and natural resources contributes to the development of sustainable buildings.	There was little incentive to use energy efficiently in South Africa because the country is acquainted to a low cost of electricity.	Deploying sustainable building in the local context will provide an avenue to obtain energy-efficient structures.
Thatcher and Milner (2012)	Gauteng	The impact of a ‘green’ building on employees’ physical and psychological wellbeing	Psychological and physical wellbeing, GreenStar accreditation; Indoor environmental quality	To compare overtime those who moved into South Africa's first GreenStar-accredited building and those who did not.	GB did not significantly improve physical or psychological wellness or perceived productivity.	Future works should provide better design features that can generate significant results for occupants wellbeing
Ross, Bowen and Lincoln (2010)	Western Cape	Sustainable housing for low-income communities: Lessons for South Africa in local and other developing world cases	Low-income settlements, sustainable construction, sustainable development	To look into instances of affordable, sustainable housing in South Africa and other emerging nations.	The success of sustainable housing depends on user acceptance and support, as well as sufficient funding.	There is need to address the housing demands of marginalised communities via a wholesome sustainability technique.
Ugwu and Haupt (2005)	Gauteng, KwaZulu-Natal, Western Cape	Key performance indicators for infrastructure sustainability – A comparative study between Hong Kong and South Africa	Infrastructure development, sustainability assessment, sustainable construction	To propose and verify indicators for measuring infrastructure sustainability,	The leading global sustainability metrics (economics, environment, and society) were incorporated into the indicators that were created and validated in both nations.	The selection of the appropriate indicators will be made by the project manager or other framework users, and they should be project- and country-specific.

Appendix B

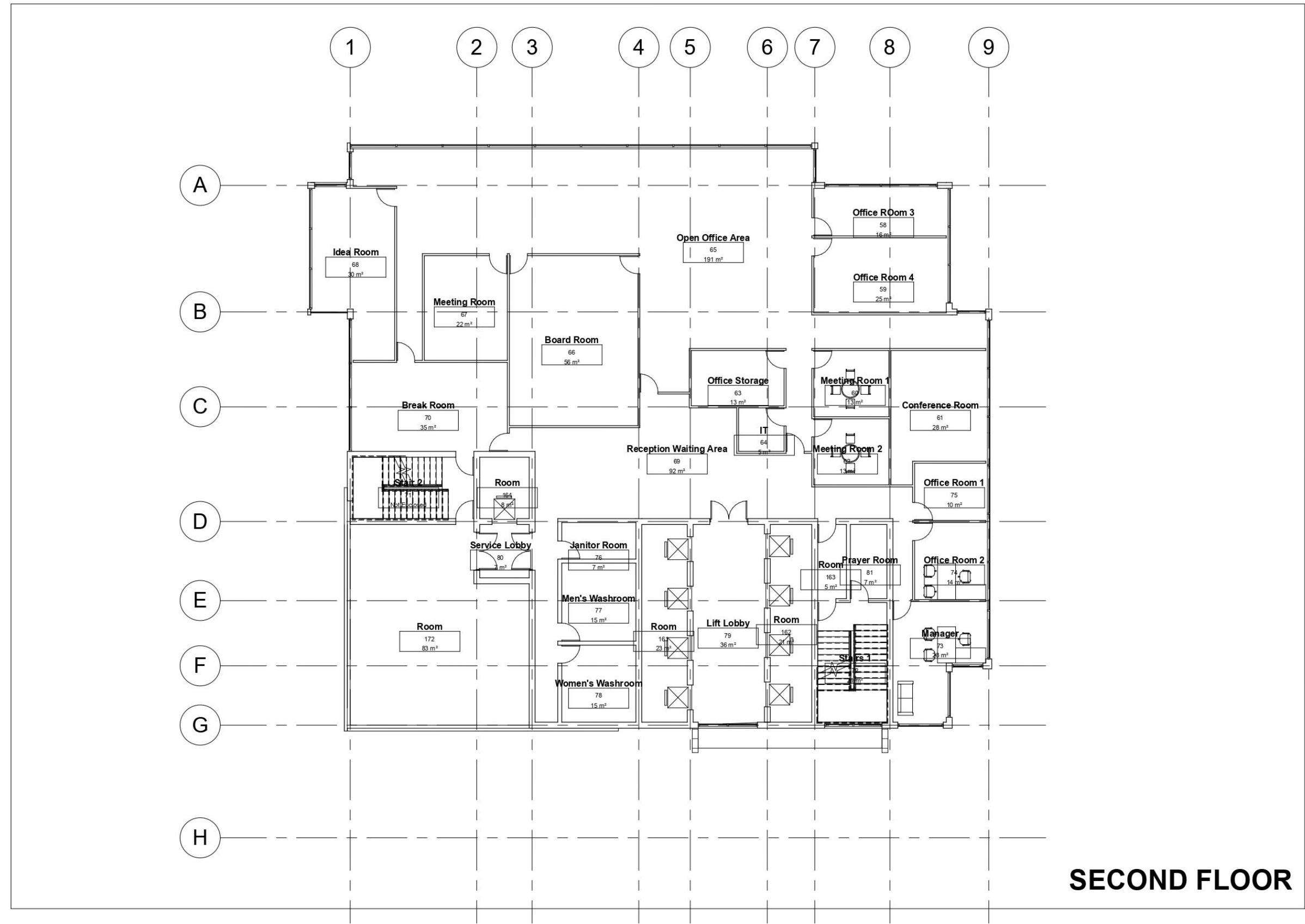
Built drawings of the office building block for green building integrated photovoltaic systems.



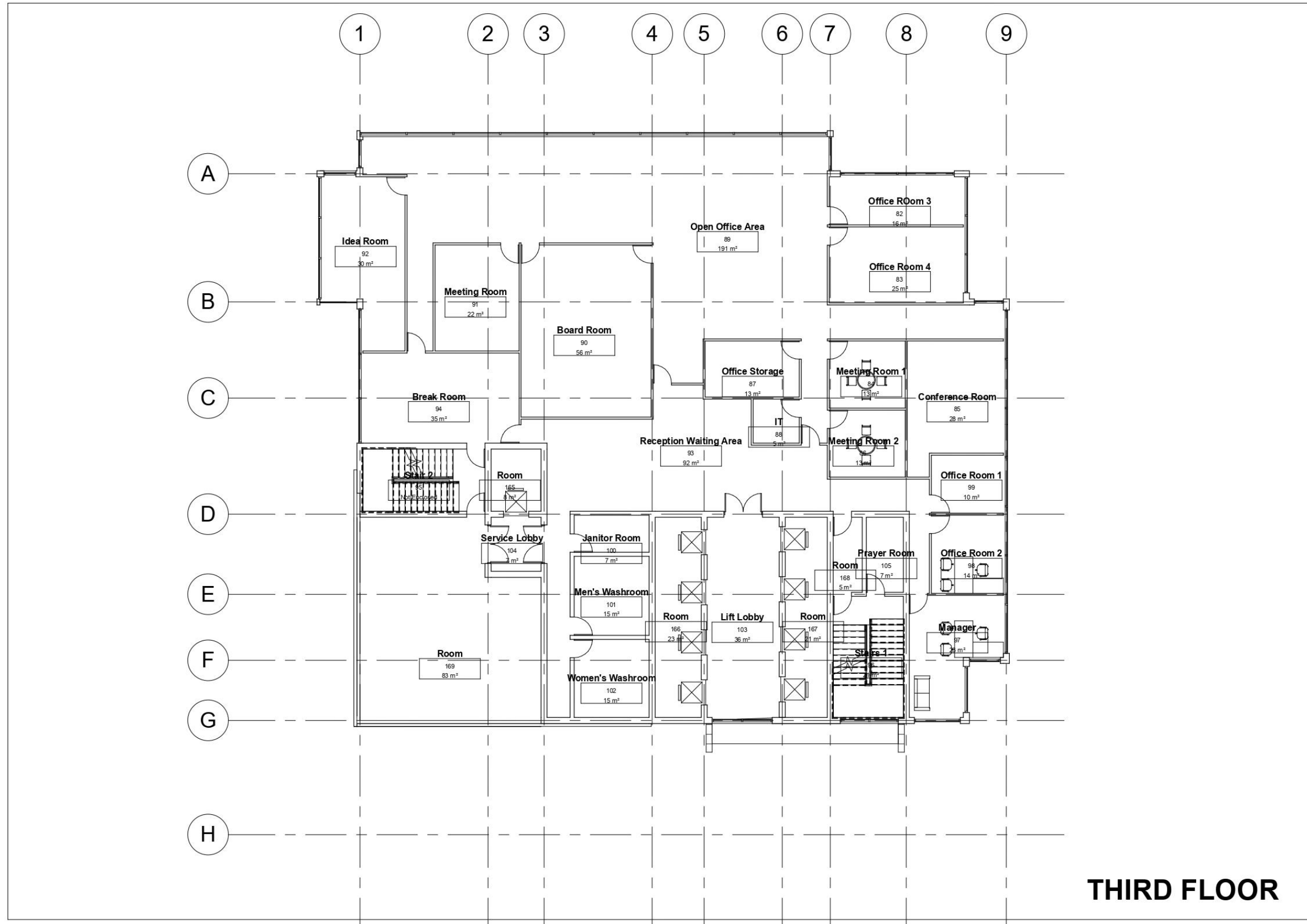
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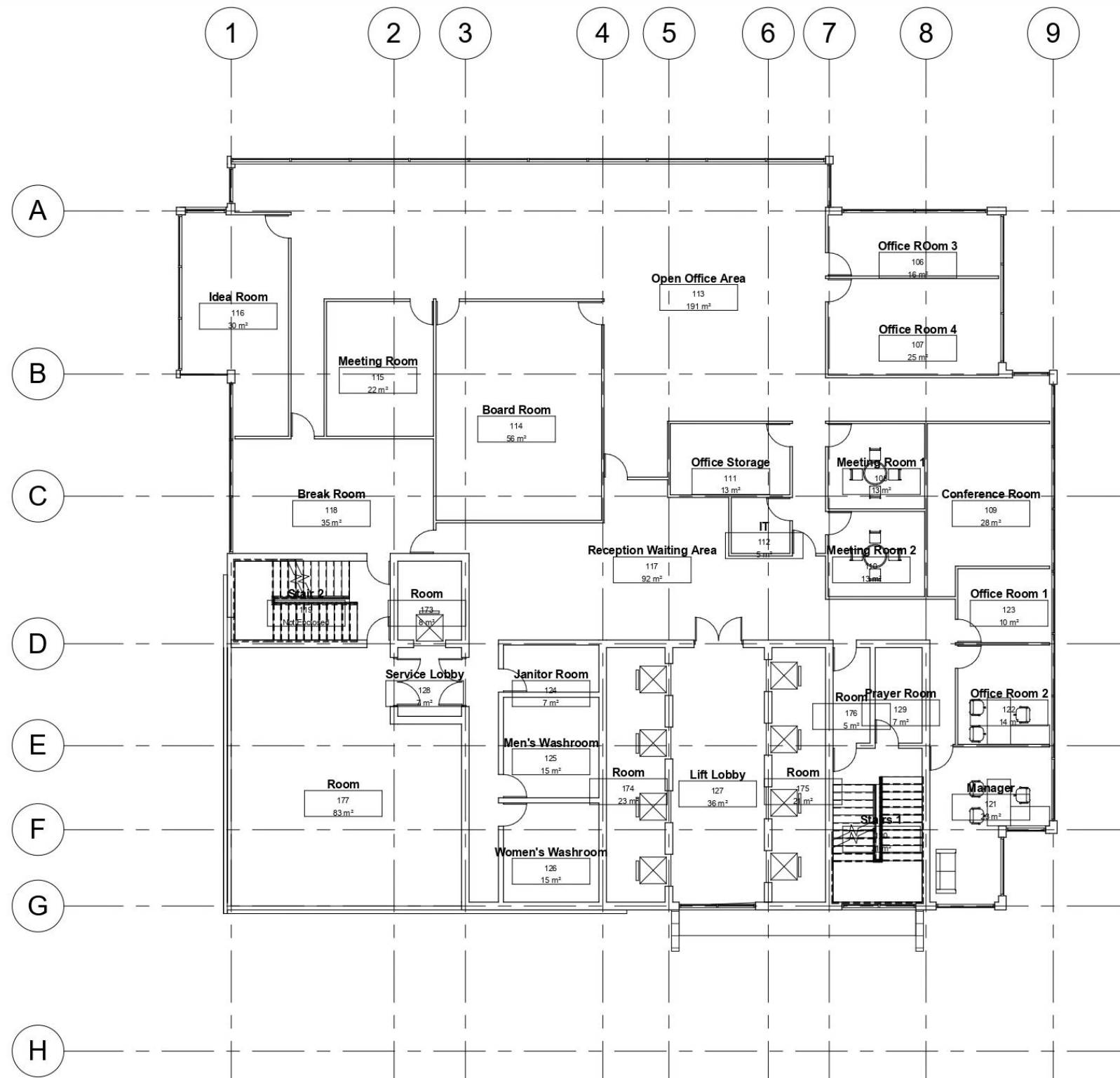
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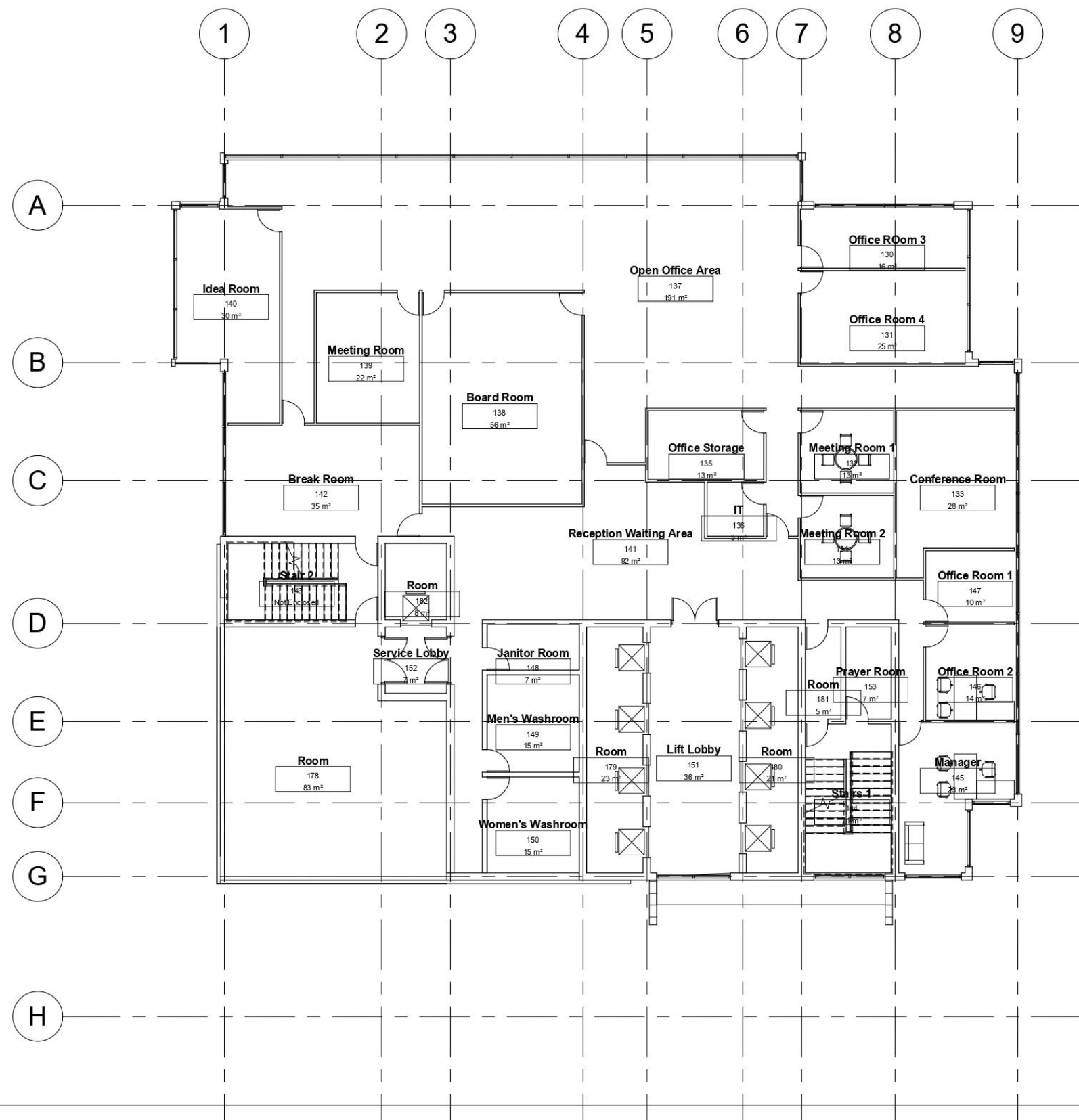
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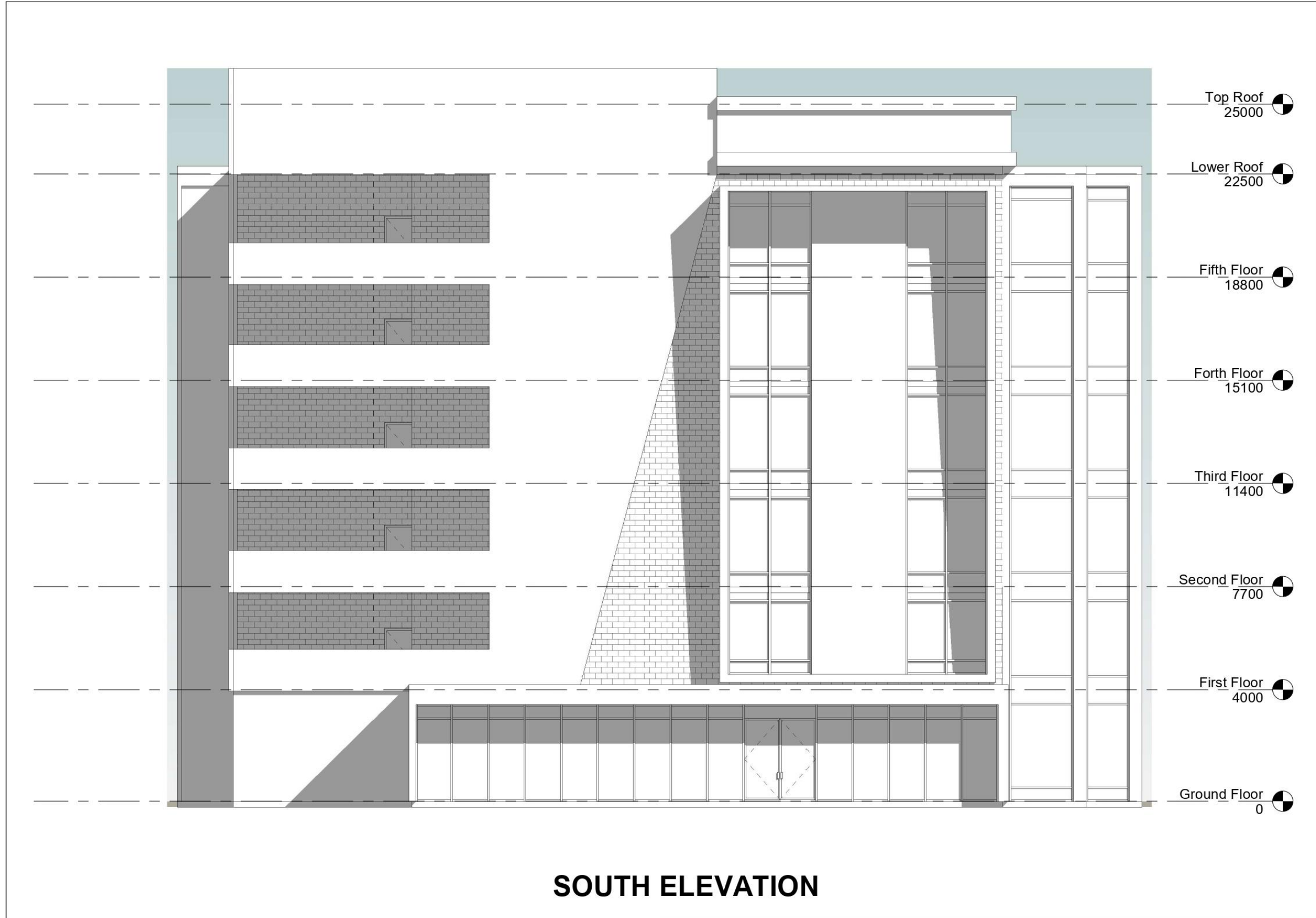
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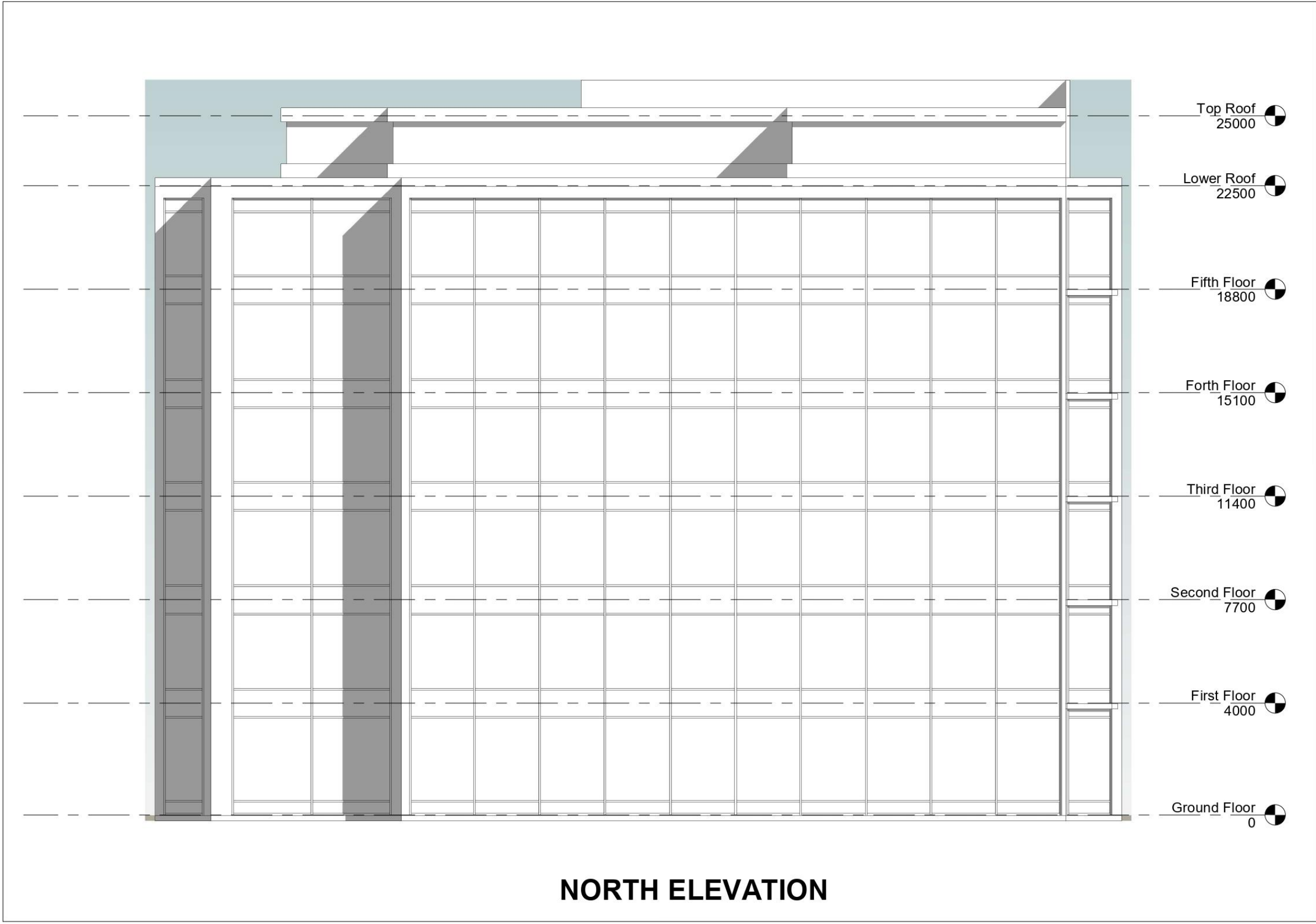
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**FIFTH FLOOR**



**SOUTH ELEVATION**







**WEST ELEVATION**



**Zertifikat  
Certificat**

**Certificado  
Certificate**

Promouvoir les plus hauts standards éthiques dans la protection des participants à la recherche biomédicale  
Promoting the highest ethical standards in the protection of biomedical research participants



**Certificat de formation - Training Certificate**

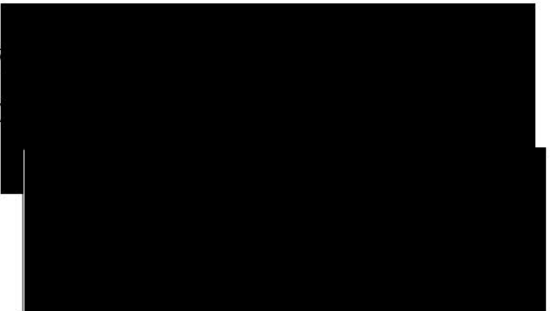
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