AN ENERGY-FOCUSED FRAMEWORK FOR INTEGRATING GREEN BUILDING RATINGS INTO LOCAL BUILDING CODES IN SAUDI ARABIA

BY

SALY ABDOU

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This thesis, written by **SALY ABDOU** under the direction of her thesis advisor and approved by her thesis committee, has been presented and accepted by the Dean of Graduate Studies, in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE IN ARCHITECTURAL ENGINEERING.**

May 7, 202

Dr. Osama Mohsen
(Advisor)

8-5-2025

Dr. Muhammad Asif
(Member)

Dr. Laith Awni Al-Hadidi
Department Chairman

Dr. Suliman Saleh Al-Homidan
Dean of Graduate Studies

Dr. Ahmed Abd El Fattah
(Member)

Date

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2025

DEDICATION

This thesis is dedicated to my beloved family, whose unwavering support and encouragement have been my greatest source of strength throughout this journey.

I also dedicate this work to research institutions, academic mentors, and colleagues who have contributed to expanding knowledge in the field of sustainable building practices.

Additionally, I extend this dedication to homeowners, construction professionals, policymakers, and all stakeholders committed to advancing energy efficiency and sustainability in the built environment. Their efforts drive the transformation toward greener and more resilient communities.

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LIST OF ABBREVIATIONS

AEC:	Architecture, Engineering, and Construction.
ASHRAE:	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BCA:	Building and Construction Authority
BEAM:	Building Environmental Assessment Method
BPS:	Building Performance Simulation.
BREEAM:	Building Research Establishment Assessment Method
CASBEE:	Comprehensive Assessment System for Building Environmental Efficiency
COP:	Coefficient of Performance
DGNB:	Deutsche Gesellschaft für Nachhaltiges Bauen
EA:	Energy and Atmosphere
EBRSs:	Environmental Building Rating
EUI:	Energy Use Intensity
GBRS :	Green Building Rating System
GCC:	Gulf Cooperation Council
GPRS:	Green Pyramid Rating System.
GUI:	Graphical interface.
HERS:	Home Energy Rating System
HQE:	High Environmental Quality
HVAC:	Heating, Ventilation and Air Conditioning
ICC:	International Code Council
IECC:	International Energy Conservation Code
IEQ:	Indoor Environmental Quality
IGBC:	Indian Green Building Council
IGCC 2015:	The 2015 International Green Construction Code
IN:	Innovation.
KFUPM:	King Fahd University of Petroleum and Minerals
KSA:	Kingdom of Saudi Arabia

LEED:	Leadership in Energy and Environmental Design
LT:	Location and Transportation
MEP:	Minimum Energy Performance
MR:	Materials and Resources.
NZEB:	Net Zero Energy Buildings.
OMBEC:	Oman Building Environmental Certification.
PRS:	Pearl Rating System.
QSAS:	Qatar Sustainability Assessment System.
RP:	Regional Priority.
SAF:	Surface-to-Volume Ratio Adjustment Factor
SBC 1001-CR:	The Saudi Green Building Code.
SBC:	Saudi Building Code
SBCNC:	Saudi Building Code National Committee.
SCE:	The Saudi Council of Engineers.
SDGs:	Sustainable Development Goals
SgBC:	Saudi Green Construction Code
SS:	Sustainable Sites
US:	United States
UN:	United Nations
WBDD:	Wet bulb degree days.
WE:	Water Efficiency.
zEPI:	Zero Energy Performance Index

ABSTRACT

Full Name : Saly Abdou

Thesis Title : An Energy-Focused Framework for Integrating Green Building Ratings into Local Building Codes in Saudi Arabia

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The construction sector consumes over 40% of global primary energy and produces nearly 30% of CO_2 emissions, underscoring the urgent need for sustainable building practices. In Saudi Arabia, buildings account for nearly 80% of total electricity consumption, emphasizing the importance of robust energy codes to meet Vision 2030 goals. This study investigated the integration of Green Building Rating Systems (GBRSs) into local codes, using the Saudi Green Construction Code (SgBC) as a case study. It benchmarked energy-related criteria in SgBC against SBC 602, Mostadam, and LEED v4.1 for homes, with a focus on energy performance metrics such as zEPI, HERS Index, EUI, and improvement over ASHRAE 90.2 baseline.

A two-set simulation-based analysis was conducted. The first set assessed an existing residential building in eight cities under different regulatory standards (SBC 602, ASHRAE 90.2, and IECC employed in LEED v4.1). The second set examined three typical buildings in three cities, evaluating the performance under diverse local jurisdictions. Each set included three phases. Findings revealed that while SBC 602 outperforms ASHRAE 90.2 in envelope performance, it falls short in overall energy efficiency in most climatic zones.

The study identified inconsistencies in Mostadam's certification outcomes against the zEPI threshold, suggesting the need for climate-specific benchmarking. A refinement phase was introduced, adjusting COP values to ensure compliance with a zEPI threshold of 50, which led to a consistent 4% improvement over ASHRAE baselines. Using national construction permit data, the analysis estimates that implementing SBC 602 could yield 182 million kWh in annual energy savings and cut CO_2 emissions by 126 million kg (11.9%) while the adjusted version boosts savings to 24.9%. Ultimately, a flexible framework was presented for enhancing building code performance, extending beyond energy efficiency to broader sustainability goals. It offers practical value for policymakers, researchers, and practitioners advancing sustainable construction.

ملخص الرسالة

الاسم الكامل: سالي احمد محمد عبده

عنوان الرسالة: إطار عمل يركز على الطاقة لدمج تصنيفات المباني الخضراء في الأكواد المحلية للبناء في المملكة العربية السعودية

التخصص: الهندسة المعمارية

تاريخ الدرجة العلمية: مايو 2025

يستهلك قطاع البناء أكثر من 40% من الطاقة الأولية العالمية، ويُنتج ما يقارب 30% من انبعاثات ثاني أكسيد الكربون، مما يبرز الحاجة الملحة إلى ممارسات بناء مستدامة. في المملكة العربية السعودية، تمثل المباني ما يقرب من 80% من إجمالي استهلاك الكهرباء، مما يؤكد أهمية وجود أكواد طاقة قوية لتحقيق أهداف رؤية 2030. تهدف هذه الدراسة إلى استكشاف تكامل أنظمة تقييم المباني الخضراء (GBRSs) مع الأكواد المحلية، وذلك من خلال استخدام الكود السعودي للبناء الأخضر (SgBC) كدراسة حالة. تم تقييم معايير الطاقة في SgBC بمقارنتها مع كود البناء السعودي SBC 602، ونظامي مستدام وLEED v4.1 للمنازل، مع التركيز على مؤشرات أداء الطاقة مثل مؤشر أداء الطاقة الصفرية (zEPI)، ومؤشر نظام تقييم الطاقة للمنازل (HERS)، وكثافة استخدام الطاقة (EUI)، ومستوى التحسين مقارنة بخط الأساس الخاص بـ ASHRAE 90.2. تم إجراء تحليل محاكاة يتكون من مجموعتين. قامت المجموعة الأولى بتقييم مبنى سكني قائم في ثماني مدن وفقًا لمعايير تنظيمية مختلفة (SBC 602 ، ASHRAE 90.2، وIECC المستخدم في LEED v4.1). بينما تناولت المجموعة الثانية ثلاث مبانٍ نموذجية في ثلاث مدن، مع تقييم الأداء ضمن سياقات تنظيمية محلية متنوعة. وتضمنت كل مجموعة ثلاث مراحل.

أظهرت النتائج أن SBC 602 يتفوق على ASHRAE 90.2 في أداء الغلاف الخارجي، لكنه يتراجع في كفاءة الطاقة الشاملة في معظم المناطق المناخية. كما كشفت الدراسة عن تفاوت في نتائج اعتماد مستدام مقارنة بعَتَبَة zEPI، مما يشير إلى ضرورة تطوير نموذج تقييم مناخي مخصص .وقد تم إدخال مرحلة تحسين، تم فيها تعديل قيم معامل الأداء (COP) لضمان الامتثال لعتبة zEPI عند 50، مما أدى إلى تحسين بنسبة 4% مقارنة بخط الأساس الخاص بـ ASHRAE 90.2.

وباستخدام بيانات تصاريح البناء الوطنية، قدرت الدراسة أن تطبيق SBC 602 قد يحقق وفراً سنوياً في الطاقة يصل إلى 182مليون كيلوات / ساعة، ويخفض انبعاثات ثاني أكسيد الكربون بمقدار 126 مليون كيلوجرام (11.9%)، بينما يرفع الإصدار المحسَّن من الوفورات إلى 24.9%. وفي الختام، قدمت الدراسة إطاراً مرناً لتحسين أداء كود البناء، يتجاوز كفاءة الطاقة ليشمل أهداف الاستدامة الأشمل، ويوفر قيمة عملية لصناع القرار والباحثين والممارسين العاملين على تعزيز البناء المستدام.

CHAPTER 1

INTRODUCTION

1.1 Background

Green building rating systems (GBRS) have played a crucial role in advancing sustainability within the construction sector [1]–[3]. Despite their widespread adoption, the actual impact of these systems on the overall building stock remains relatively small [4]. This is evident in the limited percentage of globally certified buildings under these systems, indicating a gap between certification and widespread implementation.

One promising strategy for closing this gap is the integration of green building principles, particularly those related to energy efficiency, into local building codes [5]. Doing so offers a practical path to scaling sustainability efforts across the construction industry.

This research investigates the feasibility and benefits of aligning local building codes with GBRS to enhance energy performance in residential buildings. The study focuses on the Saudi Green Building Code (SgBC), the Mostadam rating system, and LEED v4.1 for homes as primary reference points. Through comparative analysis, the research identifies energy-related gaps in SgBC and proposes targeted enhancements informed by LEED and Mostadam standards.

The investigation emphasizes energy efficiency as a critical factor in reducing the environmental footprint of buildings and supporting Saudi Arabia's strategic energy goals.

The study evaluates how integrating proven energy-focused practices from international and national rating systems can improve the effectiveness of SgBC. This alignment is vital in addressing the high energy demand and resource intensity of the building sector, thereby strengthening the regulatory framework for sustainable construction in the Kingdom.

1.2 Problem Statement

The construction industry significantly impacts environmental degradation and resource depletion despite global efforts toward sustainable development. Integrating green building practices into local building codes is still a challenge, as many green building rating systems, such as Saudi Arabia's Saudi Green Construction Code (SgBC) and Mostadam, are not yet fully coordinated or consistent with one another.

This research aims to investigate the state of the art of the effective integration of GBRSs into local building codes, focusing on the SgBC as a case study. This study analyzed and benchmarked the key factors of the SgBC against the SBC 602 and main well known GBRSs such as Mostadam and LEED v4.1 for homes. By comparing these systems, this research seeks to propose improvements for the current SgBC. These improvements were assessed through a case study evaluated using different scenarios. The study measured these improvements to evaluate their feasibility, ultimately promoting sustainable building practices and reducing the environmental impact of the construction sector in Saudi Arabia.

1.3 Significance of the Research

This research is significant as it bridges the gap between the theoretical implementation of GBRSs and their actual impact on the sustainability of the building stock. The research

aims to develop a comprehensive framework for integrating the GBRSs into local building codes, with the SgBC as a case study. This framework is crucial for overcoming existing barriers to the widespread adoption of green building practices. The findings have the potential to significantly enhance sustainable measures across the built environment, ensuring that sustainability is not just a voluntary practice but a mandated standard within the construction industry. This research could lead to substantial improvements in environmental performance and energy efficiency in Saudi Arabia's building sector.

1.4 Research Objectives

This study aims to achieve the following three key objectives:

1. Identify gaps and areas for improvement in energy-related criteria through a comparative analysis of SgBC, SBC 602, Mostadam, and LEED v4.1 for homes.
2. Evaluate energy performance outcomes by aligning SBC 602 and SgBC with Mostadam and LEED's sustainability benchmarks, supplemented by an assessment of energy savings and CO_2 emissions reduction.
3. Develop a systematic framework for integrating GBRS energy efficiency practices into local building codes to enhance residential building sustainability.

1.5 Scope and Limitation

The scope of this thesis centers on enhancing the integration of the Mostadam green building rating system into the Saudi Green Construction Code (SgBC). This process includes identifying opportunities and strategies for integration in terms of sustainable

construction approaches. While the primary focus is on the Saudi context, the research may also draw broader insights from global sustainable construction practices.

Focus Area: This study specifically examines the design and construction phases of building development, as these stages present the most significant opportunities for implementing sustainable practices at the foundational level. The research focuses exclusively on residential buildings across all climatic zones of Saudi Arabia, given this sector's substantial environmental footprint - particularly in terms of energy consumption and carbon emissions.

The investigation concentrates primarily on energy efficiency considerations, as optimizing energy performance represents a critical pathway for reducing environmental impacts and improving sustainability in Saudi Arabia's residential construction sector. This focus aligns with the nation's strategic energy conservation goals and the pressing need to address the building sector's resource intensity.

However, several inherent limitations must be acknowledged:

1. Geographic Focus: This research is primarily focused on Saudi Arabia, which may limit the generalizability of the findings to other regions with different regulatory structures, cultural dimensions, or socio-economic conditions.

2. Time Constraints: Due to the timeframe of this study, a detailed analysis of long-term impacts and trends resulting from integrating green building rating systems with local codes was not possible.

3. Data Availability: The availability and accessibility of relevant data, such as case studies and expert discussions, restricted the comprehensiveness and depth of the research findings.

4. Regulatory Complexity: The complexity of local building codes and regulatory policies may pose challenges in summarizing the entire integration and alignment process, especially since sustainability practices are constantly evolving.

1.6 Research Methodology

This study adopts a structured, multi-phase methodology to assess the impact of green building rating systems and evaluate the potential benefits of integrating these systems into local building codes. The research design comprises six key phases, as illustrated in Figure 1, ensuring a systematic and evidence-based approach.

- **Literature Review:** The study begins with an extensive review of existing literature to analyze the influence of green building rating systems on sustainability practices, the barriers to their adoption, and the feasibility of embedding these standards into building regulations. This phase establishes theoretical foundation and identifies critical research gaps.

- **Case Study Selection:** Based on the literature review, relevant building codes and rating systems are selected as case studies for in-depth examinations. The selection criteria prioritize codes with measurable sustainability impacts and applicability to different regulatory environments.

- **Comparative Analysis:** A comparative assessment is conducted to evaluate variations in implementation effectiveness, compliance mechanisms, and enforcement strategies across different codes. This phase highlights key gaps and opportunities for enhancing sustainability integration.

- **Simulation and Validation:** To test the identified gaps, a simulation model is developed, assessing the performance of selected building codes under different scenarios. The results are validated against real-world data to ensure reliability.

- **Enhancement and Impact Analysis:** The validated findings undergo enhancements, incorporating energy savings and CO2 emissions assessment to determine energy efficiency gains, and carbon reduction potential. This phase ensures that proposed improvements are both practical and sustainable.

- **Framework Development and Recommendations:** A structured framework is formulated to guide the integration of green building rating systems into local codes. The study concludes with actionable policy recommendations and future research directions to support wider adoption of sustainable construction practices.

This methodological approach ensures a rigorous, data-driven analysis, combining theoretical insights with empirical validation to advance sustainable building practices. Figure 1 provides a detailed flowchart of the research process.

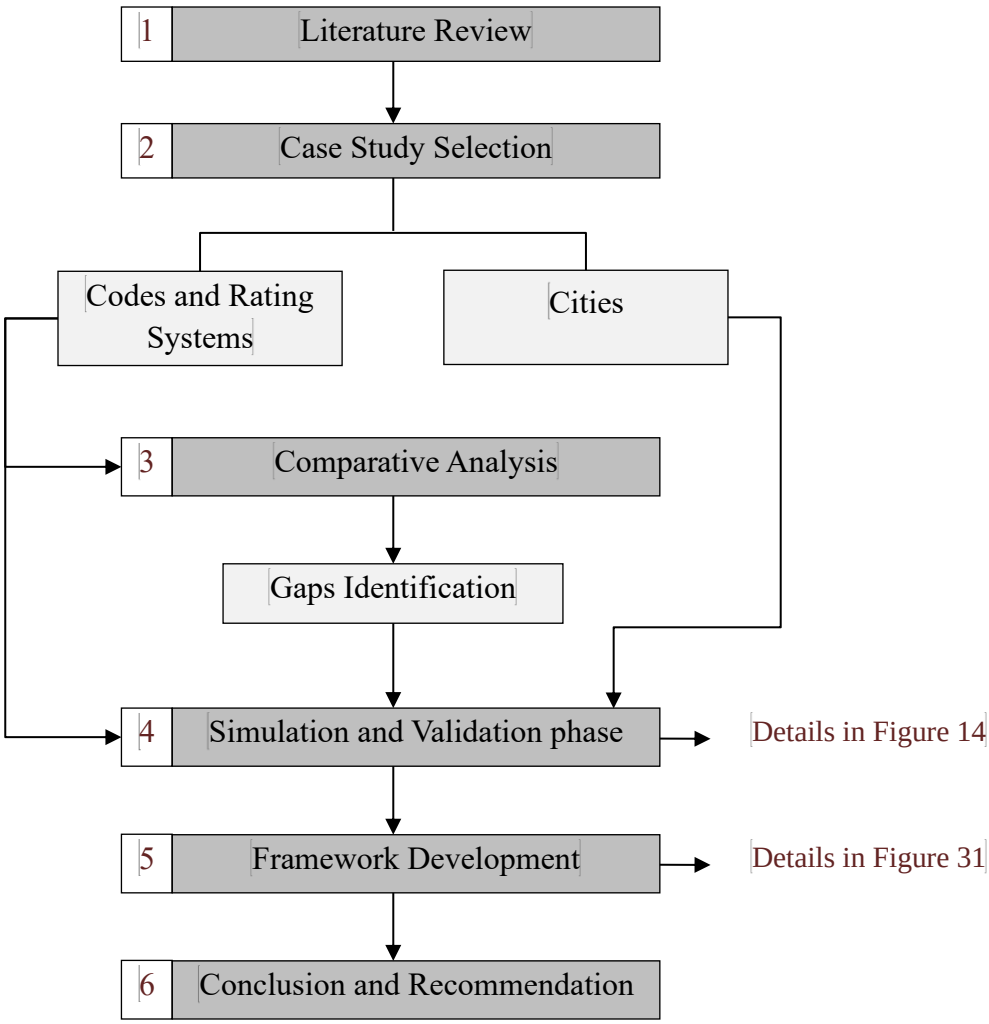


Figure 1: Research methodology Flowchart

1.7 Structure of the Thesis

To achieve the research objectives, this thesis is divided into six chapters that deal with a particular area of concern, as shown in Figure 2.

Chapter 1 provides background information, outlines the problem statement, significance of the study, research objectives, scope and limitations, and methodology, which provides an overview of the entire research journey.

1Chapter 2 conducts a comprehensive review of literature on GBRSs and the issues relating to developing and implementing them and an overview of local building codes as well as how to incorporate GBRSs with local codes, specifically in Saudi Arabia.

Chapter 3 presents a comparative analysis of different regulatory frameworks, identifying gaps and areas for improvement within the Saudi Building Code (SBC).

Chapter 4 examines the simulation phase across various scenarios, beginning with the selection of energy modeling software and identifying the existing model to be used. It then analyzes the results to propose modifications for enhanced performance.

Chapter 5 introduces the developed framework for effectively integrating green building rating systems into local building codes and offers a versatile methodology for researchers, policymakers, and industry practitioners, with potential applications extending beyond energy efficiency.

0Finally, Chapter 6 concludes the thesis by reviewing and summarizing key findings, discussing implications of these findings, and policy recommendations are proffered. It also acknowledges the study's limitations and suggests directions for future research.

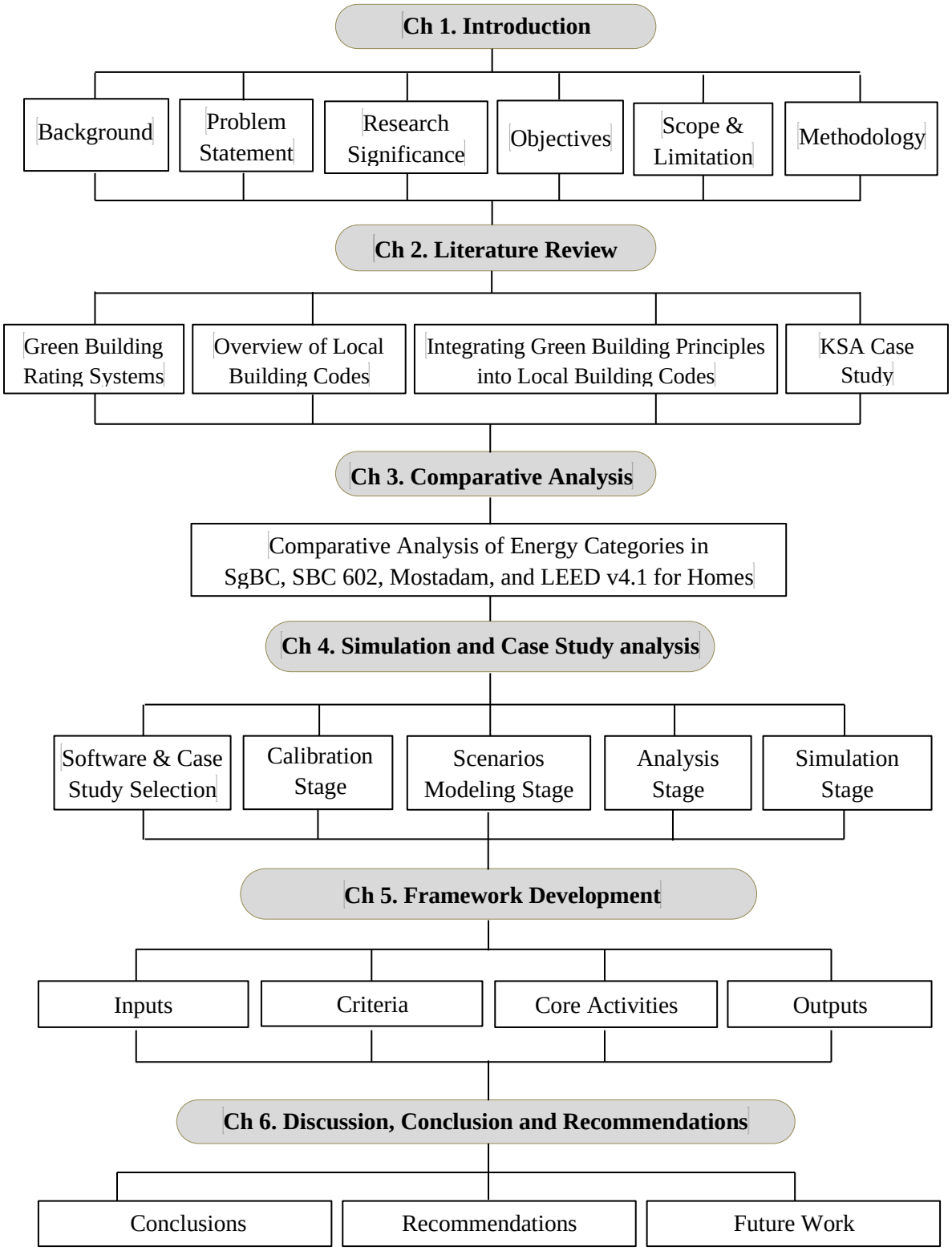


Figure 2: Thesis Structure

CHAPTER 2

LITERATURE REVIEW

The construction sector utilizes over 40% of the world's primary energy and is a significant contributor to nearly 30% of total global Carbon Dioxide (CO_2) emissions. This emphasizes its essential role in addressing worldwide energy concerns and the resulting challenges of elevated sea levels and climate change [6]. Climate change stands as the primary environmental challenge globally, leading to significant alterations in weather patterns [7].

Sustainability has evolved into a strategic necessity for nearly every industry and business [8]. Viewed as a multifaceted concept, sustainability includes environmental, economic, and social dimensions. The UN defines sustainability as meeting address current needs without compromising the ability of future generations to meet their own [9]. Sustainable or green building practices can yield advantages regarding building performance. Globally, decision makers have implemented a variety of initiatives to encourage and encourage these practices [10]. Globally, organizations have made concerted efforts to integrate sustainability into their management practices [11]. In 2015, the United Nations formally embraced the 2030 Agenda for Sustainable Development, which serves as a blueprint for global action. This agenda is composed of 17 Sustainable Development Goals (SDGs), as depicted in Figure 3 [12]

Figure 3: The 17 Sustainable Development Goals (SDGs)

The SDGs are instrumental in evaluating and shaping diverse sustainability strategies and initiatives, which have the potential to substantially decrease the overall contribution of buildings to global warming [13]. Governments have formulated their strategies and policies, keeping the SDGs in mind, with sustainable buildings playing a vital role [14]. The SDGs constitute a major global initiative aimed at steering the world towards sustainability and building resilience [15]. Nations and international organizations have implemented standards, codes, and certification systems to encourage the adoption of sustainable building practices [15]. Enhancing sustainability can be achieved through building certifications, which serve as significant benchmarks for decision-makers and practitioners in developed nations [16].

2.1 Green Building Rating Systems

Green building codes have been established to elevate sustainability and performance standards within the AEC industries. These codes outline the minimum requirements to

protect the environment, public health, safety, and welfare by mandating measures designed to minimize a building's negative impacts while enhancing its positive effects on the environment and its occupants [1]. The green certification system involves a detailed assessment to verify adherence to various pertinent requirements, both directly and indirectly. Over the past two decades, building certification systems have been implemented in numerous countries.

Worldwide, rating systems for various types of buildings are utilized to measure their sustainability levels. These systems differ from one country to another, taking into account factors like energy and water consumption, indoor environmental quality, social aspects, and economic conditions [13]. There are believed to be about 600 different green rating systems in use around the world [17]. Moreover, comparing all available certification systems is challenging due to differences in their parameters, structures, and weighting criteria [18].

2.1.1. Development of Rating Systems

Over the years, Green Building Rating Systems (GBRSs) have been introduced and continuously evolved to meet varying demands and advancements [19],[20]. BREEAM "Building Research Establishment Assessment Method" is recognized as the pioneering rating tool for evaluating building performance against specific target values across various criteria [21]. Furthermore, a variety of programs, including LEED "Leadership in Energy and Environmental Design" in the United States, LEED Canada, HQE "High Environmental Quality" in France, DGNB "Deutsche Gesellschaft für Nachhaltiges Bauen e.V." in Germany, Green Star in Australia, Green Star in New Zealand, CASBEE "Comprehensive Assessment System for Building Environmental Efficiency" in Japan,

BEAM "Building Environmental Assessment Method" in Hong Kong, and BCA "Building and Construction Authority" Green Mark Scheme in Singapore, are actively employed to assess building performances [22]. Table 1 contains some of the existing green building rating systems ordered based on the starting year.

Table 1: Example of existing green building rating systems

Country	GBRS Name	Organization	Starting	Version
United Kingdom	BREEAM	BRE	1990	International
Switzerland	Minergie ECO	MINERGIE	1998	National
United States	LEED	US Green Building Council (USGBC)	1998	International
Taiwan	EEWH	Architecture and Building Research Institute	1999	National
United States	Green Globes	Green Building Initiative	2000	National
Japan	CASBEE	Japan Sustainable Building Consortium	2001	National
India	IGBC	Indian Green Building Council	2001	National
Canada	LEED Canada	Canada Green Building Council	2002	National
South Korea	G-SEED	Ministry of Land, Infrastructure, and Transport	2002	National
Australia	Green Star	Green Building Council of Australia	2003	National
Italy	ITACA	IISBE Italia	2004	National
Canada	Green Globes Canada	Green Building Initiative	2004	National
Singapore	Green Mark	Building and Construction Authority	2005	National
China	Three-Star System	Chinese Ministry of Housing and Urban-Rural Development	2006	National
Italy	LEED Italia	Italy GBC	2006	National
India	GRIHA	The Energy and Resources Institute	2007	National
Germany	DGNB	German Sustainable Building Council	2008	International
Brazil	AQUA-HQE	Fundação Vanzolini	2008	National

Country	GBRS Name	Organization	Starting	Version
Portugal	SBToolPT	iiSBE PT	2009	National
Austria	TQB 2010	OGNB	2010	National
Czech Republic	SBToolCZ	IISBE Czech/CIDEAS	2010	National
Spain	BREEAM ES	ITG	2010	National
United Arab Emirates	Estidama	Abu Dhabi Urban Planning Council	2010	National
The Netherlands	BREEAM NL	Dutch GBC	2011	National
Norway	BREEAM NW	Norwegian GBC	2011	National
Spain	VERDE	Spanish GBC	2011	National
Sweden	BREEAM SE	Swedish GBC	2011	National
	Miljöbyggnad	Swedish GBC	2011	National
Switzerland	BREEAM CH	DIFNI	2011	National
United Kingdom	CEEQUAL	BRE	2011	International
Germany	BREEAM DE	TÜV SÜD DIFNI	2011	National
Hong Kong	BEAM Plus	BEAM Society	2010	National
United States	WELL	International WELL Building Institute	2014	International
United Kingdom	HQM	BRE	2015	National

LEED is the world's leading rating system for the design, construction, and operation of high-performance green buildings. With its different adaptations tailored to specific project types, LEED provides a structured approach to assessing sustainability across diverse building contexts. One such adaptation, LEED v4.1 for homes, focuses specifically on the residential sector, offering tools and metrics to evaluate the energy and environmental performance of homes.

2.1.2. LEED V4.1 for Homes

Over the past 18 years, successive versions of LEED have continuously advanced the global green building market, resulting in more than 197,000 projects registered and certified globally, covering over 29 billion square feet of space in 186 countries and territories [23], [24].

LEED offers a total of 110 points, with a minimum of 40 points required for certification, and the projects go through a verification and review process by GBCI. The certification is divided into four levels based on the number of points earned [23] as shown in Figure 4.

Figure 4: LEED Certification Levels [24]

The most recent version of the LEED (Leadership in Energy and Environmental Design) rating system currently available is LEED v4.1. Its technical development focused on four primary goals: maintaining leadership in the industry, enhancing the system's achievability, broadening its market applicability, and ensuring performance can be effectively measured [23]. The LEED v4.1 system was first announced on April 2, 2019, and became available in the market shortly thereafter [24]. The next iteration, LEED v5, is expected to be released for market adoption in 2025 [25].

Due to the scope of the research, this study focuses on LEED V4.1 for homes that evaluates projects based on nine categories, each contributing a specific percentage towards the total certification score. These categories collectively guide the design and construction of sustainable buildings, with a strong emphasis on energy performance and environmental impact [23]:

1. Integrative Process (IP): **2 points** - To optimize opportunities for the cost-effective implementation of integrated green design and construction strategies through details collaboration of stakeholders.
2. Location and Transportation (LT): **10 points** - Focuses on sustainable site selection and reducing the environmental impact of the development footprint.
3. Sustainable Sites (SS): 5 points - Encourages the conservation of ecosystems by reducing pollution and the responsible use of land during construction.
4. Water Efficiency (WE): **15 points** - Aims to minimize water use and promote efficient water management in buildings.
5. Energy and Atmosphere (EA): **40 points** - The largest category, emphasizing energy efficiency, the reduction of greenhouse gas emissions, and the use of renewable energy sources.
6. Materials and Resources (MR): **12 points** - Focuses on the sustainable use of building materials and waste reduction.
7. Indoor Environmental Quality (IEQ): **16 points** - Ensures the health and comfort of building occupants through better indoor air quality and environmental controls.
8. Innovation (IN): 6 points - Rewards creative and innovative sustainable strategies that go beyond the standard LEED requirements.
9. Regional Priority (RP): **4 points** - Offers additional points for addressing environmental priorities specific to the project's location.

This study focuses on the Energy and Atmosphere category (EA). The category is divided into 3 prerequisites and 4 credits. The prerequisites are, namely, minimum energy performance (MEP), energy metering and education of the homeowner, tenant or building

manager. While the Credits are Annual Energy Use, Efficient Hot Water Distribution System, HVAC Start-Up Credentialing and Refrigerant Management [26]. A further depth of the study is examining the prerequisite of minimum energy performance and the credit, Annual Energy Use.

To meet the MEP requirements, the LEED v4.1 classified the building to new construction and Major renovation. While our study is limited to new construction. The rating system refers to meeting all mandatory measures by ENERGY STAR for homes. This certification program depends on the Home Energy Rating System (HERS) index target which every new home is expected to meet in the United States (US). However, an adjustment factor called the Surface-to-Volume Ratio Adjustment Factor (SAF) is used outside the US. Other requirements for a new construction include the use of ENERGY STAR-certified appliances and the use of a fully ducted system.

As defined by LEED v4.1 [26], the credit Annual energy use has the highest possible point of 36 in this category, which aims to enhance the home's energy efficiency and minimize its greenhouse gas emissions. This credit provides two options, namely LEED Energy Budget and HERS index, as a means of benchmarking the energy use in the building. The HERS Index can be used for new construction or major renovation. Due to the flexibility of the HERS index, this study adopted the HERS index for new construction. The annual energy usage of the new construction is defined to achieve a HERS rating index of 70 and below to achieve points as described in Table 2.

Table 2: Points for achieving HERS index rating

HERS index	HERS points below ENERGY STAR HERS Index Target	Points	HERS index	HERS points below ENERGY STAR HERS Index Target	Points
70	0	10	56	14	23
69	1	11	54	16	24
68	2	12	52	18	25
67	3	13	50	20	26
66	4	14	45	25	27
65	5	15	40	30	28
64	6	16	35	35	29
63	7	17	30	40	30
62	8	18	25	45	31
61	9	19	20	50	32
60	10	20	15	55	33
59	11	21	10	60	34
58	12	22	5	65	35

The HERS index is determined using Equation 1. However, to account for differences in home size relative to a standard reference home, the adjusted HERS must be calculated as specified in Equation 2.

$$\text{HERS Index} = \frac{\text{Energy Use of Rated Home}}{\text{Energy Use of Reference Home}} \times 100 \qquad \text{Equation 1}$$

$$\text{SAF Adjusted HERS Target} = \text{Baseline HERS Target} \times \text{SAF Factor} \qquad \text{Equation 2}$$

- Baseline HERS Target = Standard ENERGY STAR HERS Index based on climate zone.
- SAF Factor = "Size Adjustment Factor" Adjustment based on home size relative to a benchmark size based on the ENERGY STAR homes Program.

To calculate SAF, Equation 3 shall be used to modify the required efficiency level based on the home's conditioned floor area (CFA).

$$SAF = [CFA_{\text{Benchmark Home}} / CFA_{\text{Home To Be Built}}]^{0.25} \quad \text{Equation 3}$$

- CFA Benchmark Home = Conditioned Floor Area of the Benchmark Home
- CFA Home To Be Built = Conditioned Floor Area of the Home to be Built

To calculate the Conditioned Floor Area ($CFA_{\text{Benchmark Home}}$), the number of bedrooms needs to be counted, and based on the following Table 3 the $CFA_{\text{Benchmark Home}}$ can be determined.

Table 3: Benchmark Home Size [27]

Bedrooms in Home to be built	0	1	2	3	4	5	6	7	8
$CFA_{\text{Benchmark Home}}$ (sq. ft.)	1000	1000	1600	2200	2800	3400	4000	4600	5200

2.1.3. Regional and Local Rating Systems

Countries that did not develop their building rating systems initially had to select from various assessment options to align with the growing global emphasis on environmental building assessment such as those in Table 1. Research has promoted the adoption of local systems that are better suited for achieving regional objectives compared to alternative assessment options [19], [20]. Assessment methods for buildings are crafted with specific regions in mind, and various factors can hinder their direct application elsewhere. These factors encompass geographical positioning, climatic conditions, technological and material availability, policy landscapes, cultural dynamics, and population sizes [28], [29].

Various nations, including those in the Gulf region, have tailored their regulations, codes, and rating systems to suit their unique local characteristics and contexts [20]. Certain

countries, including the UAE, have pioneered the development of their own EBRS, such as the Pearl Rating System (PRS), also known as the Estidama tool, introduced in 2008. This effort is in line with Abu Dhabi's 2030 vision to emerge as a global sustainable city [30]. The Pearl Rating System (PRS), also known as the Estidama tool, amalgamated elements from widely used rating systems like LEED and BREEAM, tailored to local needs and national priorities. Similarly, other Gulf countries have followed suit in advancing environmental building assessments, exemplified by the Qatar Sustainability Assessment System (QSAS) was introduced in Qatar in 2009, while the Oman Building Environmental Certification (OMBEC) was established in Oman in 2017 [13] Also noteworthy is the Green Pyramid Rating System (GPRS), serving as Egypt's environmental assessment method [31].

2.1.4. Adoption and Implementation Challenges

The adoption of green buildings is gradually increasing at a steady pace, with a more pronounced trajectory observed in new construction projects and standalone high-income housing developments. However, it is concerning to note the relatively minor attention given to the existing building stock [32]. The use of assessment methods is generally voluntary; however, some countries mandate their application for publicly funded projects [33].

The study conducted by Ismail and Ismail et al. has outlined various obstacles hindering the application of LEED, which may also apply to other rating systems. These include minimal financial incentives and stakeholder involvement, the time-consuming and expensive nature of the process of certification, along with the complexities associated with credit requirements and the absence of decision support tools for certain credits.

Additionally, there's a concern about the scarcity of eco-friendly materials in local markets that meet the necessary requirements [34], [35].

The trend toward embracing green buildings is prominent in new construction projects and upscale standalone housing developments. However, it is concerning to observe the relatively minor focus on the existing building stock, despite comprising the vast majority (almost 90%) of all buildings in the region [32]. In Saudi Arabia, sustainable urban planning strategies have been introduced as part of efforts to mitigate climate change. Nevertheless, the execution of these strategies is still in its nascent stages, particularly in urban greening, with green buildings only beginning to gain recognition [28].

2.2 Overview of Local Building Codes

In general, building codes are compulsory documents at the national or international level that outline requirements for the Architecture, Engineering, and Construction (AEC) industry. Governments and authorities mandate stakeholders to adhere to specific building codes and standards [36]. Utilizing and enforcing building codes represents a potential solution for integrating environmental, safety, and other essential measures into construction practices [14]. The Saudi Council of Engineers (SCE) defines building codes as a collection of documents, requirements, rules, regulations, standards, and best practice recommendations that collectively serve as the primary reference for building and construction [37]. Building codes are designed to establish the minimum standards necessary to ensure safety and protect public health [28]. Building codes and regulations have shifted towards being less prescriptive and more focused on functionality or performance-based criteria [38].

Building codes outline the construction techniques, materials, and energy/water usage standards for buildings. However, updating these codes is hindered by inadequate or low-quality climate data in various regions globally. While countries such as the UK have started integrating climate change adaptation into their building codes, developing nations are also striving to implement mandatory and voluntary codes. Nonetheless, the incorporation of climate regulations remains inadequate in many developing countries [39]. Codes specify how buildings should be constructed, the types of materials to be used, and the levels of energy and water consumption, among other factors. Typically, building codes rely on historical data to anticipate potential issues throughout a building's life cycle. However, the current lack of climate data or the poor quality of such data in many regions makes it difficult to update these codes effectively [39].

Globally, some countries, like the UK, have integrated climate change adaptation into their building codes and standards. However, while there is a growing effort in developing nations to introduce both mandatory and voluntary building codes, the incorporation of climate regulations remains insufficient in many of these countries [39]. Building regulations are among the most effective and cost-efficient strategies for reducing greenhouse gas emissions in both new and existing buildings. In the Middle East, numerous governments are adopting policies aimed at fostering a more sustainable built environment. In GCC countries, these initiatives have intensified over the past decade [40], marked by the introduction of new or revised building codes and the development of Demand Side Management strategies as per in Table 4.

Table 4: Examples of building regulations in the GCC region

Country/City	**Regulation**	**Rating System**	**Most Recent Edition**	Ref.
Dubai	Al Sa'fat	Sa'fa	2017	[41]
Abu Dhabi	Estidama	Pearl Rating System	2016	[42]
Ras Al Khaimah	Barjeel Green Building Regulation	-	2018	[43]
Kuwait	Energy Conservation Code of Practice	-	2014	[44]
Kingdom of Saudi Arabia	Saudi Green Building Code	Mostadam Rating System	2018	[45]
Kingdom of Bahrain	Unified Guidebook of Building Permit Regulations	-	2019	[46]
Qatar	Global Sustainability Assessment System	-	2019	[47]

Two more pertinent facets of the development of the existing codes need more investigation. One is the shift, already accomplished by Qatar, from prescriptive to mix legislation (prescriptive/performance). The second is to assess, using the ASHRAE model, the advantages of various codes for residential and non-residential (including low-rise) buildings. This model was applied by the Kingdom of Saudi Arabia [40].

2.3 Integrating Green Building Principles into Local Building Codes

Studies on the integration of green building principles into regulatory frameworks have demonstrated promising outcomes, including enhanced environmental performance, decreased operational expenses, and improved occupant health and well-being [5]. By aligning local building codes with green building rating systems, cities and regions have the potential to drive significant advancements in sustainability across their building stock. However, further exploration of the feasibility, challenges, and benefits of this integration is needed to develop effective strategies for implementation.

This literature review lays the groundwork for the present study by consolidating existing insights on the influence of green building rating systems, obstacles in expanding sustainability endeavors, and the potential advantages of harmonizing local building codes with green building principles. The identified gaps emphasize the significance of this research in providing fresh perspectives and suggestions for promoting sustainability in the built environment through policy interventions and regulatory frameworks.

The Saudi Green Building Code, SgBC 1001-CR, is integrated into Chapter 10 of SBC 2018 with the aim of ensuring that buildings are designed and constructed in accordance with environmentally friendly practices. However, it's important to note that this section is voluntary and emphasizes considerations for the environment, public health, safety, and general welfare [28] [48]. The Saudi Green Building Code is also viewed as a tool to encourage the adoption of green practices [28].

2.4 KSA Case Study

Saudi Arabia is the world's top energy producer and the largest nation in the Middle East [49], covering an area of two million square kilometers [50]. Saudi Arabia is located in one of the world's most intense solar radiation zones and is renowned for its blistering climatic conditions, where temperatures can soar as high as 55°C in certain regions [51]. The average of warming in Saudi Arabia over the past four decades is 2°C, positioning the nation within a global hotspot of localized warming [52]. Saudi Arabia has a delicate ecosystem, scarce water resources, and experiences frequent coastal flooding, leading to its ranking of 84th on the 2018 Global Climate Risk Index [53].

2.4.1. Building Energy Consumption and CO_2 Emissions

The country is experiencing rising energy consumption and greenhouse gas emissions, coupled with significant demographic pressures due to a 2.3% annual population growth rate [12]. The country has an enormous ecological footprint and a large resource demand [54].

In Saudi Arabia, buildings consume more than 70% of the electricity generated [55], [56]. This energy consumption is increasing annually, as displayed in Figure 5. The total electrical energy consumption reached 327,001 gigawatt hours in 2023, marking an increase of 5.65% compared to 2022 as displayed in Figure 6.

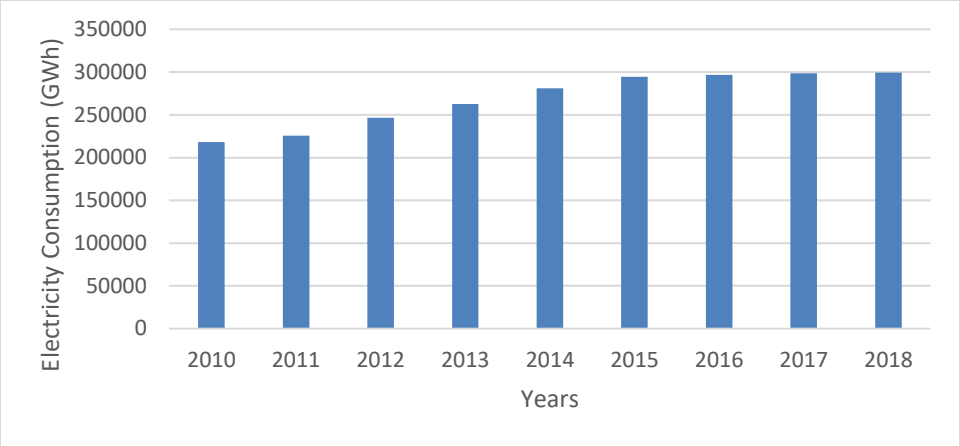


Figure 5: Annual Electricity Consumption [57]

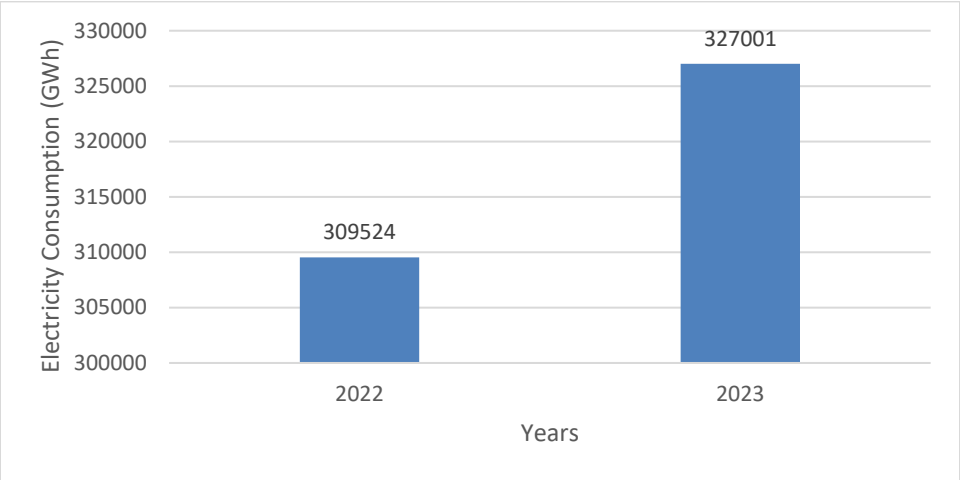


Figure 6: Total electrical energy consumption in 2022 and 2023 [57]

As shown in Figure 7, residential buildings consume the highest amount of electricity compared to other building sectors over the years. This trend is further supported by the 2023 electricity consumption breakdown (Figure 8), where residential buildings account for 46.72% of the total electricity usage. Figure 9 illustrates the trends in electricity consumption across different regions over time.

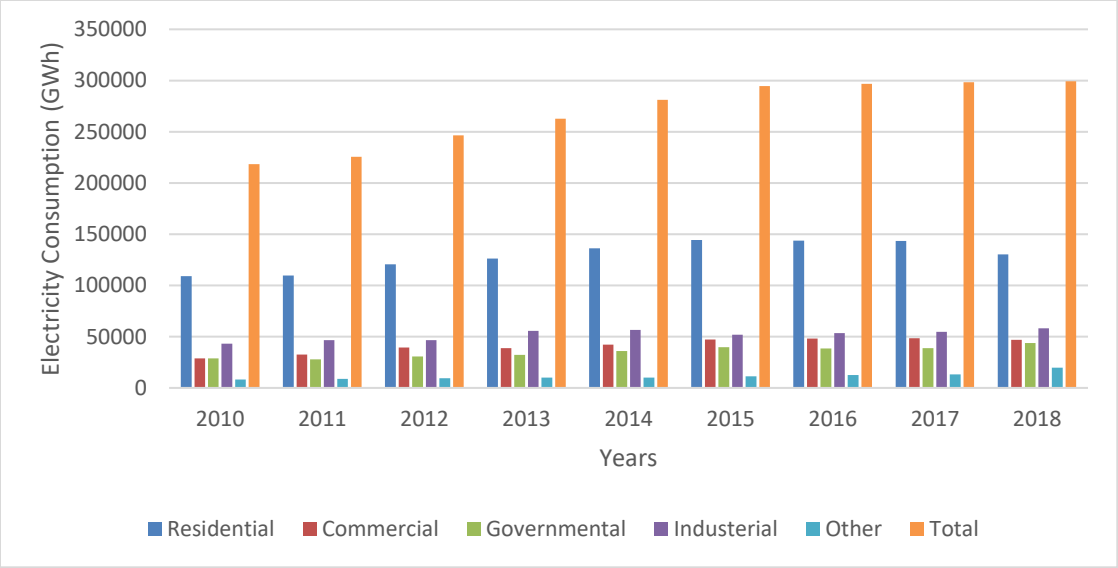


Figure 7: Consumption of Electrical Energy by Sectors over years [57]

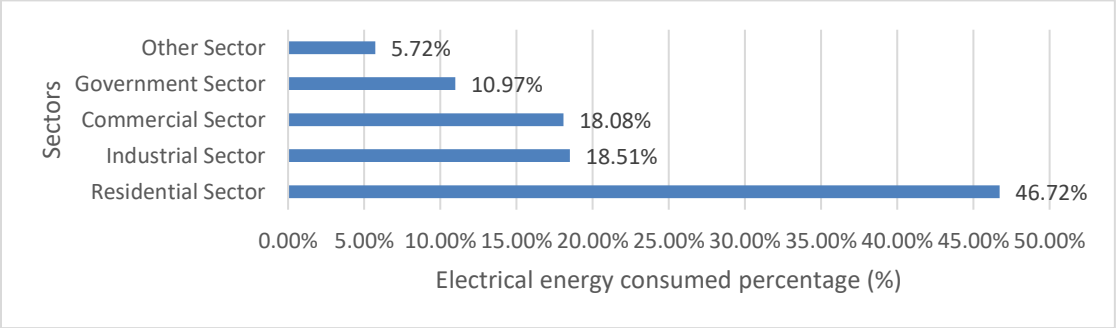


Figure 8: Electrical energy consumed by consumption category in SA in 2023 [57]

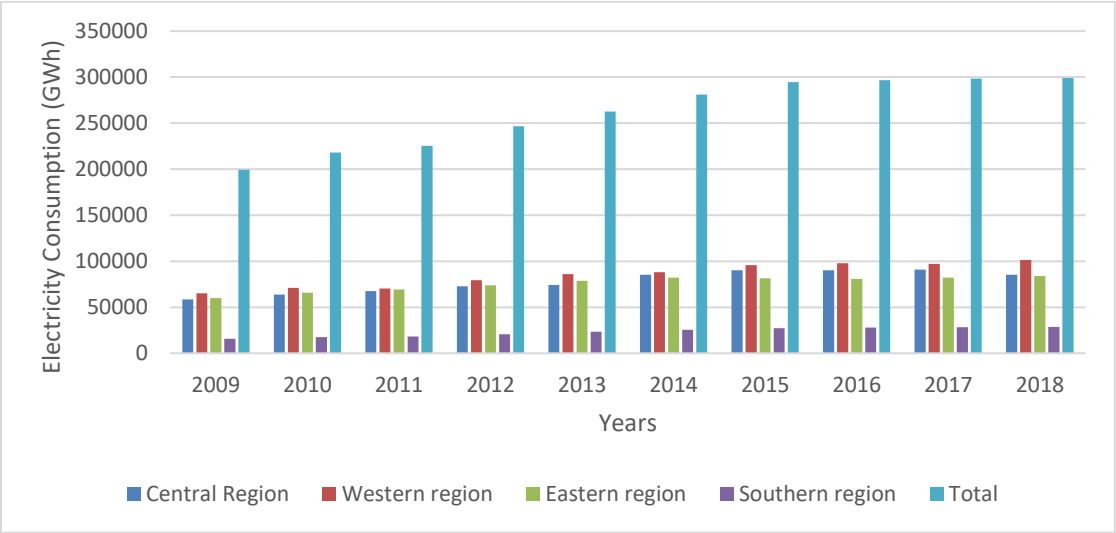


Figure 9: Consumption of Electrical Energy by Regions over years [57]

This expenditure is anticipated to rise further with the emergence of new mega projects [58]; Hence, integrating sustainability strategies could result in substantial enhancements within the AEC industry. Saudi cities have experienced significant growth, accompanied by continuous infrastructure development. However, the rapid expansion and urban sprawl have led to various consequences [59][18]. In response, the Kingdom of Saudi Arabia (KSA) has introduced Vision 2030, a strategic roadmap designed to guide the nation's economic and developmental future, anchored in three core themes: a vibrant society, a thriving economy, and an ambitious nation [45]. This vision outlines the country's long-term objectives, aiming to balance urban progress with sustainable and inclusive development.

2.4.2. Saudi Building Code (SBC)

In 2010, the Kingdom of Saudi Arabia (KSA) launched an energy efficiency program called the Saudi Energy Efficiency Center through the Council of Ministers' resolution. What followed was the enactment of the Saudi Building Code (SBC) 601 and 602 in 2017 aimed to regulate the energy performance of residential low-rise buildings and commercial high-rise buildings [40]. These codes had yearly released publications, with the latest edition released in 2019 [60].

In 2018, the Saudi Building Code National Committee (SBCNC) released the updated Saudi Building Code (SBC) and introduced a five-year implementation plan [61]. The plan commenced on June 20, 2018. Since then, the code has been mandated for all building types, including government buildings, high-rise structures, hospitals, hotels, mosques, sports arenas, educational facilities, malls, communication towers, industrial buildings, high-risk structures, wedding halls, cinemas, theaters, healthcare centers, motels,

residential buildings, entertainment venues, business facilities, airports, banks, TV stations, and post offices [37]. The Saudi Building Code (SBC) comprises a collection of legal, administrative, and technical regulations that define the minimum standards for building design and construction in the Kingdom of Saudi Arabia (KSA) [48]. In the Saudi Building Code (SBC), essential engineering discipline codes are obligatory, including:

- The general building code (SBC-201-CR)
- The structural building code (SBC-301-CR)
- The electrical building code (SBC-401-CR)
- The mechanical building code (SBC-501-CR)

Moreover, the SBC-1001-CR (SgBC) encompasses various aspects such as material resource conservation and efficiency, site development and land use, reduction of energy consumption and CO_2 emissions, enhancement of water resource quality and efficiency, improvement of indoor environmental quality and comfort, inspection, commissioning, operation and maintenance, as well as considerations for existing buildings and their site development [28].

A study carried out before the launch of the Saudi Green Building Code shows that it is possible to reach an energy savings of 45%, improving the thermal characteristics of the buildings' envelope [62].

2.4.2.1. Saudi Green Construction Code (SgBC)

The Saudi Building Code for Green Construction (SgBC) is an incorporated part of SBC 2018; however, this part is voluntary [61] and was designed to protect the environment, public health, safety, and general welfare by establishing requirements that

minimize negative impacts and enhance positive impacts of the built environment on both the natural environment and building occupants. This code is meant to be used alongside other Saudi codes, serving as an overlay document rather than a standalone construction regulation. Permits are not to be issued based solely on this code, and it does not override or replace safety, health, or environmental requirements specified in other applicable codes or ordinances [63].

The 2015 International Green Construction Code (IGCC 2015), published by the International Code Council (ICC), serves as the foundation for this code. The Saudi Building Code National Committee (SBCNC) collaborated with the ICC to adapt their materials to fit the local construction needs and regulatory requirements of Saudi Arabia. The ICC is not responsible for any modifications or changes made by SBCNC to these documents. Numerous alterations and adjustments were made to the original IGCC 2015 to align with local climate, materials, construction practices, and regulations [63]. The SgBC covers various aspects including site development and land use, conservation and efficient use of material resources, reduction of energy consumption and CO_2 emissions, water resource quality and efficiency, indoor environmental quality and comfort, as well as commissioning, inspection, operation and maintenance, and the development of existing buildings and building sites [64].

2.4.3. Mostadam for Residential Buildings

Mostadam was created by the Saudi Ministry of Housing as part of the "Sustainable Building" program. It serves as a comprehensive sustainability certification and rating system aimed at guaranteeing the enduring sustainability of residential buildings in Saudi Arabia. Mostadam covers various sustainability issues crucial to the KSA and aligns with

the goals of Vision 2030 [13]. Mostadam is designed to be in harmony with the Saudi Building Code (SBC), specifically the Saudi Green Construction Code (SgBC). It has been meticulously developed to surpass the minimum requirements of the SBC, guaranteeing an elevated standard of sustainability for residential buildings [65].

Figure 10 illustrates the alignment between the SBC and Mostadam for residential buildings, a crucial representation considering that the rating's criteria stem from the three most pertinent chapters of the SBC. Specifically, SBC 501, 601, and 1001 serve as the foundational pillars upon which Mostadam was developed [48].

Figure 10: Relationship between SBC and Mostadam for residential buildings [48]

Mostadam has five different rating levels namely Green, Bronze, Silver, Gold and Diamond, the levels and the attainable points for this level as summarized in Table 5.

Table 5: Mostadam rating levels [48]

Points	Rating Level
20 - 34	Green
35 - 49	Broze
50 - 64	Silver
65 -79	Gold
80 -100	Diamond

Mostadam is divided into two rating categories, namely the design and construction (D+C) and Operation and Existing (O+E). Each of this rating categories have their peculiar credit categories, the D+C has nine primary categories, which are site sustainability, transportation and connectivity, religion and culture, Energy, water, Health and comfort, Materials and Waste, Education and Innovation, and Policies, Management and Maintenance as defined in Mostadam [66], [67]. For the Mostadam O+E, there are seven major categories namely, Policies, Management and Maintenance, Energy, Water, Health and Comfort, Education and Innovation, Site sustainability, Transportation and Connectivity [67]. Both have an accumulated score of 100 as the maximum; the minimum achievable score to earn the green certification level is 20 to 34 as shown in Table 5. In both rating system categories, energy credit categories have the highest point with 27 in the D+C and 29 in the O+E.

Hence, this study primarily focuses on the Energy category of the Mostadam D+C with full concentration of a new building. However, the Energy category of the Mostadam O+E was used to align the operation used of the building as stated. Both categories have mandatory credits called Keystone credits, there are 12 in numbers resulting in 20 points

in the Mostadam O+E [67]. In the case of D+C the keystone credits are peculiar to the rating level planned to achieve. There are two rating certificates in the D+C namely the Design rating certificate and the construction rating certificate. While for the O+E there is the operation rating certificate subjected to recertification every 5 years.

To get the points of Mostadam D+C, the improvement percentage over ASHRAE baseline has to be calculated as per Equation 4, and the points are awarded based on the Table 6.

$$\% \text{ Improvement} = \frac{\text{Baseline Annual Energy Consumption} - \text{Proposed Annual Energy Consumption}}{\text{Baseline Annual Energy Consumption}} \quad \text{Equation 4}$$

Table 6: Points available for percentage improvement achieved over ASHRAE baseline

Percentage Improvement	Points Achieved
0%	5
5%	6
10%	7
15%	8
20%	9
25%	10
30%	11
35%	12
40%	13
45%	14
50%	15

To get the points of Mosadam O+ E, the points are awarded based on the EUI as mentioned in the Table 7.

Table 7: Energy Benchmarks

Energy Efficiency Rating		Annual Energy Consumption [1,2]	Credits Points Available
Band A+		Less than 120 kWh/m2	7
Band A		Less than 150 kWh/m2	5
Band B		Less than 185 kWh/m2	3
Band C		Less than 225 kWh/m2	1
Band D		Less than 265 kWh/m2	0
Band E		Less than 320 kWh/m2	0
Band F		More than 320 kWh/m2	0

The diverse climatic conditions in Saudi Arabia pose a challenge to the implementation of unified assessment certification systems nationwide. Therefore, certification systems should account for these climatic variations across the country. Globally, there is increasing recognition of the environmental impacts of buildings, leading to a rising interest in adopting sustainable building practices [28]. Mostadam cannot be universally applied across all regions of Saudi Arabia without yielding potentially misleading results. This limitation arises from the diverse characteristics of the country's internal regions [68].

In Saudi Arabia, the Mostadam Certification System was introduced a few years ago. Research by Al-Surf et al. examined the awareness of AEC stakeholders in Saudi Arabia regarding green certification systems, revealing an improvement in awareness compared to earlier studies. Additionally, 57.5% of respondents preferred to use LEED, while the remaining 42.5% opted for locally recognized systems within Mostadam. The study further concluded that the preference for LEED stems from its evolution over more than 25 years and the presence of LEED-accredited experts in the market, whereas the Mostadam system is still in its early stages [13].

2.4.4. Climatic Zones

In KSA, a great variation in terms of climatic aspects exists; it was therefore divided in several ways into zones with common climatic characteristics. One of those classifications recommended that KSA can be classified into five climatic zones represented by Dhahran, Guriat, Riyadh, Jeddah, and Khamis Mushait, with the fact that the Empty Quarter is an uninhabited region, as shown in Figure 11 [69].

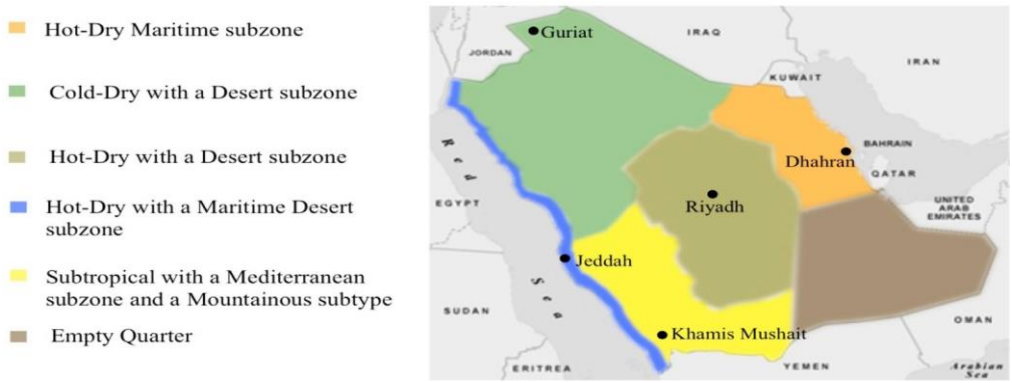


Figure 11: Climatic zone classification of KSA for building energy modeling [69]

Another study classified Saudi Arabia into five major climatic zones using wet bulb degree days (WBDD), based on temperature and moisture levels. These zones were represented by key cities: Jeddah (extremely hot and humid), Riyadh (extremely hot and dry), Al-Wajh (very hot and humid), Taif (very hot and dry), and Tabuk (hot and dry), with further subdivision into 10 sub-zones [70]. The study also highlighted regional energy trends, noting that Jizan has the highest Energy Use Intensity (EUI), while Abha exhibits the lowest energy consumption [70]. Building on this research, the cities selected for the current study include Jeddah, Riyadh, Al-Wajh, Taif, Tabuk, Jizan, and Abha, along with Dhahran—the location of the existing building under analysis.

CHAPTER 3

COMPARATIVE ANALYSIS

The integration of sustainable practices into a building code requires a thorough comparative analysis of the existing regulatory frameworks and rating systems. This process helps in identifying gaps, aligning sustainable principles with mandatory requirements, and ultimately refining the local code to establish a sustainable building code.

In this study, a comparative analysis was conducted on four key regulatory frameworks and rating systems in Saudi Arabia:

- Saudi Building Code (SBC 602): The energy conservation chapter of the national building code.
- Saudi Green Building Code (SgBC): The voluntary green building code in Saudi Arabia.
- Mostadam: The national green building rating system for residential buildings in Saudi Arabia.
- LEED v4.1 for homes: An internationally recognized green building rating system.

This comparison focuses only on the energy category, analyzing all credits, sub-credits, and technical requirements in these frameworks to determine the points of alignment and

gaps that need improvement. The findings of this comparison serve as the foundation for improving the SgBC by incorporating the best practices from these frameworks.

Additionally, since Saudi Arabia has already integrated sustainability into its building code through the SgBC, this comparison assesses whether the current green building chapter sufficiently promotes sustainability or requires further enhancements. LEED v4.1 is also included in the analysis to benchmark international standards and best practices.

3.1 Comparative Analysis of Energy Categories in SBC, SgBC, Mostadam, and LEED

Table 8 presents the similarities, differences, and gaps across SBC 602, SgBC, Mostadam, and LEED v4.1 for homes in terms of energy efficiency requirements and performance criteria. The table evaluates each framework based on various credits and sub-credits, covering aspects such as:

- Energy performance benchmarks
- Envelope and HVAC system requirements
- Renewable energy integration
- Building commissioning
- Energy metering and monitoring

Table 8: Comparative Analysis of Energy Criteria in SBC, SgBC, Mostadam, and LEED

Credit	Sub-Credit	SBC 602	SgBC	Mostadam	LEED v4.1 for homes
Energy Performance	Minimum Energy Performance	✓	✓ zEPI-based	✓ Keystone (Green) EUI-based	✓ EA Prerequisite
	Annual Energy Use Reduction	✓	✓ zEPI used for benchmarkin g	✓ Keystone (Green) EUI-based	✓ EA Credit
	Energy Efficiency Benchmarking	✓ Mandatory for compliance	✓ zEPI for performance comparison	✓ Keystone (Green) EUI tracking	✓ Energy Star/HERS
CO_2 Emissions from Electricity		✗	✓	✗	✗
Onsite Nonrenewable Energy Emissions		✗	✗	✗	✗
Energy Metering, Monitoring, and Reporting	Energy-Use Monitoring	✓	✓	✓ Keystone (Silver)	✓ EA Prerequisite
	Sub-Metering for Major Energy Uses	✓	✓	✓ Keystone (Silver)	✗
	Data Collection and Reporting	✓	✓	✓	✓ EA Prerequisite
Automated Demand-Response (Auto-DR) Infrastructure	Demand-Response System Implementation	✗	✓	✗	✗
	Smart HVAC Controls	✗	✓	✗	✗
	Rebound Avoidance Strategies	✗	✓	✗	✗
Building Envelope Systems	Insulation and Fenestration Criteria	✓	✓	✓ Keystone (Green)	✓ EA Prerequisite

Credit	Sub-Credit	SBC 602	SgBC	Mostadam	LEED v4.1 for homes
	Shading Devices for Fenestration	✓	✓	✓	✓ EA Prerequisite
	Air Leakage Control	✓	✓	✓	✓ EA Prerequisite)
	Thermal Performance Verification	✓	✓	✓	✕
Building Mechanical Systems	HVAC Equipment Performance Requirements	✓	✓	✓	✓ EA Prerequisite
	HVAC Piping Insulation	✓	✓	✓	✓ EA Prerequisite
	Fan Efficiency and Ductwork Testing	✓	✕	✓	✓ EA Prerequisite
	Economizers for Energy Efficiency	✓	✓	✓	✓ EA Prerequisite
Energy Systems Commissioning	HVAC System Commissioning	✓	✓	✓ Keystone (Green)	✓ EA Credit: HVAC Start-Up Credentialing
	Envelope Commissioning	✓	✓	✓ Keystone (Green)	✕ Indirectly covered
	Whole-Building Systems Commissioning	✓ Focuses on mechanical systems	✓	✓ Keystone (Green)	✕ Only HVAC commissioning
Building Electrical Power and Lighting Systems	Lighting Power Density Requirements	✓	✕	✓	✓ EA Prerequisite

Credit	Sub-Credit	SBC 602	SgBC	Mostadam	LEED v4.1 for homes
	Auto-DR for Lighting Control	☑	☑	☑	☑ EA Prerequisite
Energy Efficient Appliances	Use of ENERGY STAR or Equivalent Appliances	✕	☑	☑	✕ Considered under whole home efficiency, but no separate credit
Renewable Energy Systems	Onsite Renewable Energy Integration	☑ Encouraged but not required	☑	☑ Keystone (Green)	✕ Not explicitly listed in this LEED version
Renewable Energy Credits (RECs)		☑	✕	☑	✕
Energy Storage and Recovery Systems	Heat Recovery Systems	☑	✕	☑	☑ EA Prerequisite
	Drain Water Heat Recovery	☑	✕	☑	☑ EA Prerequisite
Ozone Impact	Use of Low-Ozone Refrigerants	☑	☑	☑ Keystone (Green)	☑ EA Credit: Refrigerant Management
Homeowner/Tenant Education	Training in Energy Use and Efficiency	✕	✕	✕	☑ EA Prerequisite
Efficient Hot Water Distribution	Efficient Water Heating System Design	☑	☑	☑	☑ EA Credit
Energy-Use Intensity (EUI)		☑	☑ zEPI referenced	☑ Explicitly uses EUI	☑ EA Prerequisite
Outcome-Based Pathway Requirements		☑	☑	☑	☑ EA Prerequisite
CO_2 Emissions Modeling		☑	☑	☑	☑ EA Prerequisite
Building Service Water Heating Systems		✕	☑	☑	☑ EA Prerequisite

3.1.1. Key Findings and Areas for Improvement in the SgBC

Based on the comparative analysis, the following gaps and improvement areas were identified in SgBC:

1. Each framework follows a different energy performance measurement approach. LEED V4.1 for homes relies on the Home Energy Rating System (HERS) Score, which is derived from Energy Star criteria, Mostadam O+E incorporates Energy-Use Intensity (EUI), which measures the total energy consumed per unit of building area (kWh/m² per year) and Mostadam D+C incorporates the percentage of the improvement compared to ASHRAE 90.2, while SBC 602 follows a prescriptive approach, requiring compliance with a predefined set of efficiency standards. And SgBC always references SBC 602 with additional performance-based criteria which is zEPI as it provides a standardized way to assess energy efficiency and compare buildings' energy consumption as it is a scale from zero (net-zero energy) to 100 (baseline energy use) as shown in Figure 12.

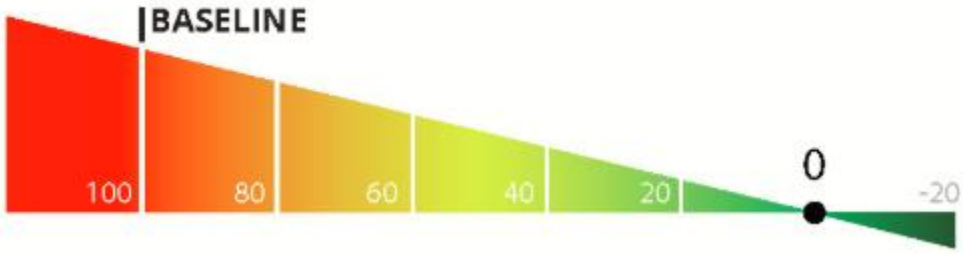


Figure 12: Zero Energy Performance Index (zEPI) scale [71]

Since the energy performance approach varies across these frameworks, a deeper analysis is needed to determine which methodology is more effective and how the best elements of each system can be integrated into the SBC.

2. Unlike SBC 602, SgBC introduces CO_2 reduction requirements, making it more performance-driven.

3. While SBC 602 sets minimum efficiency requirements, Mostadam and LEED encourage higher efficiency standards with additional credits.

4. LEED and Mostadam provide clear incentives for renewable energy, while SgBC lacks explicit requirements or incentives in this regard.

5. LEED mandates detailed energy monitoring, while Mostadam and SgBC only recommend it.

6. SBC 602 and SgBC demonstrate strong coverage of core envelope and mechanical system efficiency requirements, such as insulation, air leakage control, HVAC performance, and commissioning. However, LEED stands out by integrating additional energy systems commissioning elements and appliance-level criteria, offering a more holistic approach.

7. SgBC incorporates advanced smart energy technologies, including demand-response infrastructure, smart HVAC controls, and rebound avoidance strategies, not found in SBC 602, Mostadam, or LEED. This gives SgBC an edge in future-ready energy optimization and grid responsiveness.

8. Only LEED incorporates tenant education on energy use, reflecting a more comprehensive approach that goes beyond design and construction to address occupant behavior, an aspect that is notably absent in SBC 602, Mostadam, and SgBC frameworks.

9. Energy-efficient appliance requirements are missing in SBC 602 and LEED, while SgBC and Mostadam explicitly incorporate these standards. This limits the comprehensiveness of SBC and LEED in capturing energy savings from plug loads and user-dependent systems.

10. SBC 602 and SgBC are more aligned with local climate and regulatory conditions, while LEED follows a more generalized international framework. Mostadam acts as a hybrid, integrating local codes with global sustainability practices, especially in energy tracking through EUI and improvement metrics.

11. LEED is the only system that indirectly addresses refrigerant management through credits, while the rest treat low-ozone refrigerants as prerequisites—showing LEED's flexibility in allowing design choices while promoting environmentally responsible options.

12. SgBC and Mostadam incorporate zEPI or EUI-based performance metrics explicitly, enhancing comparability and accountability in energy modeling, while SBC relies purely on prescriptive compliance.

13. Energy storage and recovery systems such as heat recovery and drain water heat recovery, are recognized across most systems except SgBC, suggesting a gap in SgBC's treatment of energy recapture technologies.

14. Outcome-based pathway and CO_2 emissions modeling are well-represented across all systems except SBC 602, positioning SBC as the least outcome-focused framework among the four, with more emphasis on input criteria rather than measurable results.

15. Water heating distribution efficiency is missing in SBC 602, which may overlook significant thermal losses in plumbing systems. LEED, Mostadam, and SgBC recognize this through dedicated credits or prerequisites.

3.1.2. Analysis of Energy Performance Approaches

The Energy Performance approaches were selected for further analysis as the integration of Mostadam and SBC 602 into a unified framework requires a hybrid approach that balances prescriptive energy requirements with performance-based tracking methods. SBC 602 is primarily based on prescriptive requirements. In contrast, the Saudi Green Building Code (SgBC) builds upon SBC 602 by incorporating additional performance criteria, specifically the Zero Energy Performance Index (zEPI). The Mostadam rating system adopts two distinct approaches: Mostadam O+E evaluates energy performance through Energy Use Intensity (EUI) tracking, while Mostadam D+C focuses on the percentage improvement over the ASHRAE 90.2 baseline. Meanwhile, LEED v4.1 for homes evaluates energy performance using the Home Energy Rating System (HERS),

which is derived from the EnergyStar program and aligns with the International Energy Conservation Code (IECC), as illustrated in Figure 13.

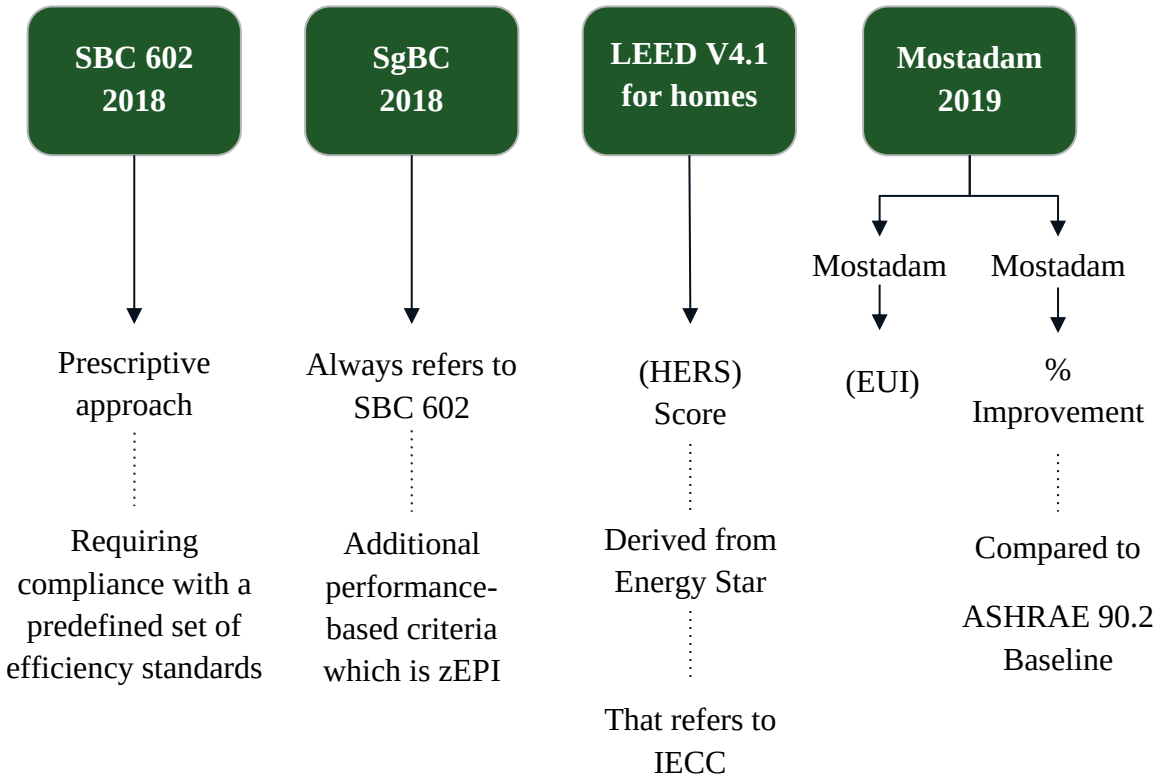


Figure 13: Energy Performance Measurement Approach

This study explores whether integrating these different approaches could lead to a more effective and sustainable energy framework for Saudi Arabia. This raises two fundamental questions:

- What led to the adoption of zEPI in the SgBC, and how does it align with existing energy performance frameworks?
- How does zEPI compare to Energy Use Intensity (EUI) in terms of accuracy, applicability, and effectiveness in tracking energy performance?

To address these concerns, a comparative assessment of EUI and zEPI was conducted to evaluate their effectiveness in measuring and tracking energy efficiency through:

1. Evaluating the effectiveness of different energy performance measurement methods, including HERS Index, zEPI, EUI, and other benchmarks.

2. Identifying and addressing gaps in the Saudi Green Building Code (SgBC) by incorporating best practices from Mostadam, LEED, and SBC 602.

3. Determining whether integrating different energy performance approaches into the Saudi Building Code (SBC 602) can enhance energy efficiency outcomes.

To achieve this, the next chapter presents a detailed simulation study comparing energy performance under various regulatory scenarios. The results will help identify the most effective approach for improving the sustainability of Saudi building codes.

CHAPTER 4

SIMULATION AND CASE STUDY ANALYSIS

This chapter presents a simulation-based analysis aimed at evaluating building energy performance across various regulatory frameworks. The overarching goal is to identify the most effective strategy for enhancing the sustainability of building codes in Saudi Arabia. Through a comparative assessment, the chapter seeks to highlight how different compliance pathways and rating systems influence energy consumption; and to provide actionable insights for aligning local codes with international best practices.

A structured and replicable methodology is essential for ensuring the accuracy and reliability of the findings. Therefore, a systematic five-stage process was designed, as outlined in the flowchart in Figure 14. This process guides the evaluation from the initial setup to the final interpretation of results. Each stage plays a critical role in ensuring that the simulation reflects realistic conditions and provides meaningful outcomes.

The process is divided into five major stages: (1) selection of the simulation software and the representative building model, (2) calibration of the model based on actual performance data, (3) development of regulatory and performance scenarios, (4) execution of energy simulations under each scenario, and (5) in-depth analysis and interpretation of the results to draw conclusions and recommendations. These stages will be discussed in detail in the following sections, with each step carefully examined to illustrate its role in the overall simulation framework and its contribution to the final outcomes.

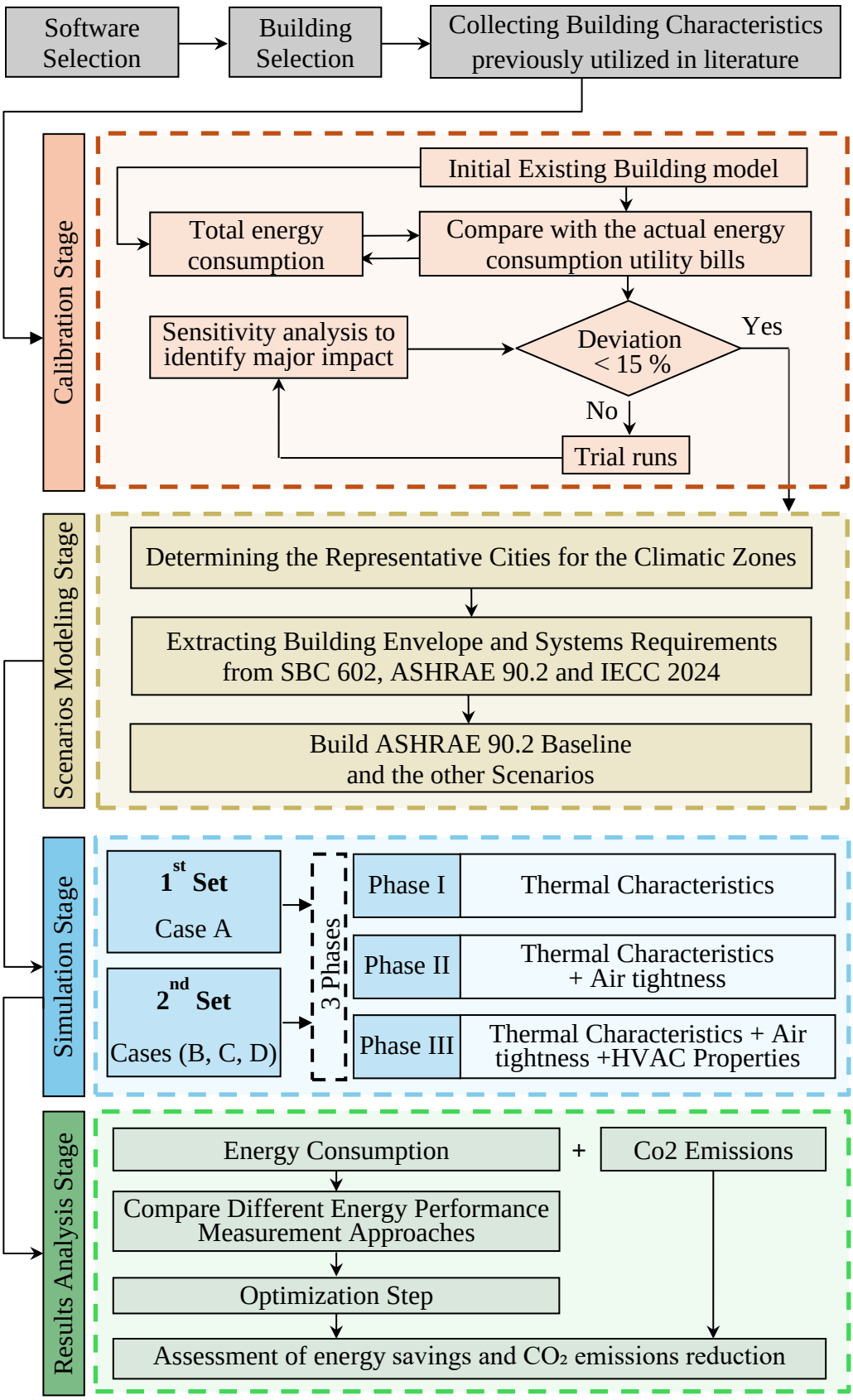


Figure 14: The Simulation chapter flowchart

4.1 Software and Case Study Selection

4.1.1 Energy Modeling Software Selection

Building simulation software tools are widely utilized by designers and engineers to explore various design possibilities while accounting for a multitude of factors. These include climate conditions, internal heat gains, building envelope properties, architectural configurations, HVAC system specifications, operational schedules, and control strategies, among other variables [72].

EnergyPlus, developed in alignment with the ASHRAE 2004 standard, is based on two tools from the 1970s: BLAST and DOE2. This software produces detailed and accurate models of building energy consumption. It facilitates the calculation of critical parameters related to visual and thermal comfort, incorporating features such as HVAC systems, shading, lighting, and refrigeration systems [73], [74].

DesignBuilder, leveraging the robust EnergyPlus engine, is a versatile and advanced platform for analyzing building energy performance. It enables detailed evaluations of heating, cooling, lighting, and ventilation systems while providing insights into carbon emissions, operational costs, and daylighting efficiency. Distinguished by its intuitive interface, DesignBuilder allows users to efficiently model, assess, and optimize both the building envelope and the indoor environment. A standout feature is its capability to compare the performance of various building components, offering a clear understanding of how changes in envelope materials influence overall energy consumption, enabling informed design decisions for enhanced sustainability [74], [75]. A notable advantage of EnergyPlus and DesignBuilder is their seamless integration with AutoCAD software,

enabling efficient file import and export processes. This compatibility streamlines workflows, allowing users to incorporate detailed architectural designs directly into energy simulations and optimize building performance with ease [74]. Their utility is most pronounced when the building is pursuing a green building certification, such as LEED [76].

Attia and De Herde [77] explored the application of Building Performance Simulation (BPS) tools in the design of Net Zero Energy Buildings (NZEB). Their comparison of ten tools revealed that DesignBuilder offers the most comprehensive features for early-phase design. In addition to providing a user-friendly graphical interface (GUI) for the widely adopted EnergyPlus simulation engine, DesignBuilder complies with the requirements outlined in ASHRAE Standard 140-2011 [78], making it a robust tool for energy performance analysis. This study employed DesignBuilder version 7.0.2.6 for simulation and analysis.

4.1.2 Building Selection

The case study for this research is a three-bedroom, single-family detached house located within the King Fahd University of Petroleum and Minerals (KFUPM) campus in Dhahran, Eastern Province, Saudi Arabia. The chosen house type ranks second among housing types, accounting for 17% of total energy consumption [79] as shown in Figure 15. This housing type was chosen due to its exposure to the environment from all directions. Its model and capacity are representative of typical residential buildings in the Eastern Province, making it a suitable choice for this study. Additionally, it was previously

used as a case study by Makawi et al. in research analyzing the impact of air infiltration on energy performance in Saudi Arabia's hot-humid climate [80].

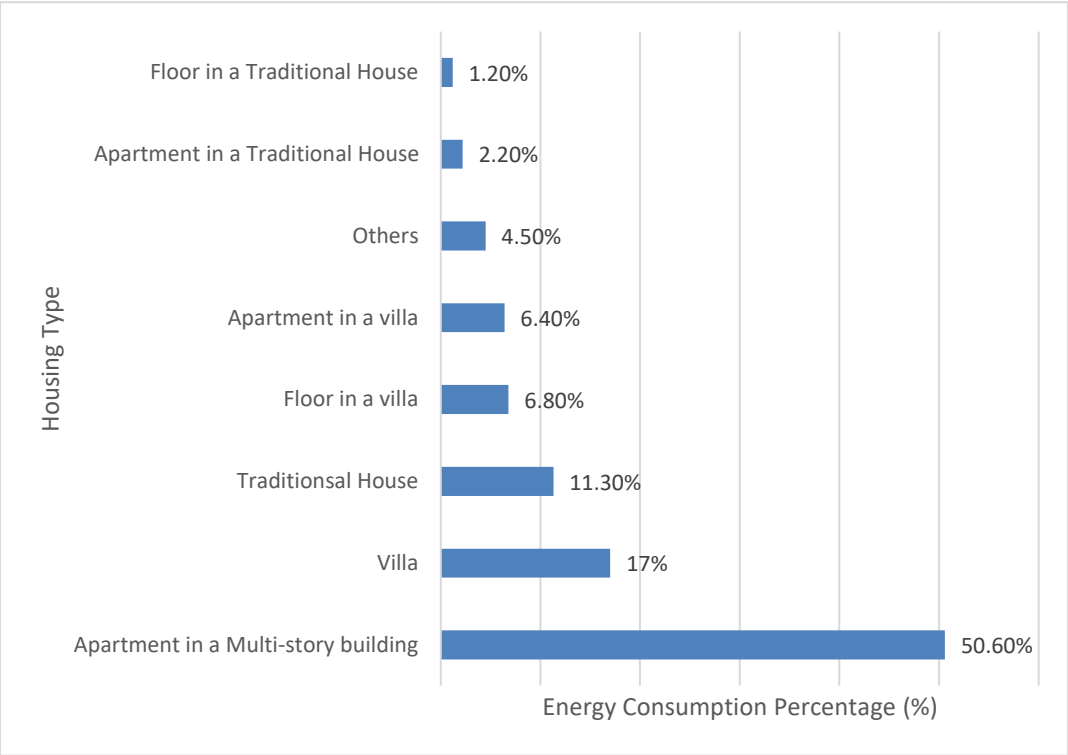


Figure 15: Energy Consumption by Housing Type in Saudi Arabia (2022) [79].

Table 9 provides a comprehensive summary of the house's characteristics, including its orientation, dimensions, envelope details, HVAC specifications, and energy performance metrics. This concise overview highlights the key parameters considered in the study.

Table 9: Summarized House Description and Simulation Details [80]

Category	**Details**			
Orientation	Southwest, approximately 212° from the true north.			
Floor Areas	▪ Ground floor: 189 m². ▪ First floor: 135 m² (Reduced due to HVAC unit space).			
Ceiling Height	2.7 meters (Both floors)			
Layout	Rectangular, as shown in Figure 17 (floor plans and elevation views).			
Envelope Components	Detailed in Table 10, summarizing the layers and U-values for walls, floors, roof, and windows.			
Cooling System	Constant-volume (CV) direct expansion package units [80]:			
	Unit's location	Capacity	Supply airflow	Outside airflow
	Ground floor	40.7 kW (11.58 tons)	8121.3 m³/h (4780 CFM)	1223.3 m³/h (720 CFM)
	First floor	27.9 kW (7.95 tons)	5402.9 m³/h (3180 CFM)	305.8 m³/h (180 CFM)
HVAC Operation	Operated 24/7 for validation purposes; the house was unoccupied during monitoring.			
Environmental Setpoints	Cooling and heating setpoints are maintained at 21°C.			
Lighting and Equipment	Excluded from the model as they were not in operation during the monitoring period.			
Simulation Validation	The base case model was validated using short-term, real-time energy consumption data.			
Annual Energy Consumption	289 kWh/m² per total building area.			
Energy Distribution	▪ 87% for cooling. ▪ 12% for system fans. ▪ 1% for heating.			

Table 10 provides a summary of the envelope components of the house, including its layers and corresponding thermo-physical properties [80], [81]. Figure 17 shows the building plans, front elevation, and a longitudinal section, while Figure 16 illustrates the extruded model used for the analysis [80].

Table 10: Envelope components details [80]

Envelope Components	Layers: Outside to Inside	U-Value W/(m2.k)
External Walls	16 mm Plaster (Dense) + 100 mm Concrete Block (Medium) + 50 mm Extruded Polystyrene + 100 mm Concrete Block (Medium) + 13 mm Plaster (Lightweight)	0.466
Floor	Glazed ceramic tiles + Cement mortar + Dense reinforced concrete + High-density polyethylene + Sand + Earth, gravel	0.792
Roof	40 mm Concrete Tiles (Roofing) + 0.2 mm Polyethylene (High Density) + 50 mm Extruded Polystyrene + 4 mm Bitumen Felt + 59 mm Cement Screed + 300 mm Reinforced Concrete (Cast, Dense)	0.539
External Windows	4 mm Glass, generic tinted + 12 mm air gap + 6 mm Glass, generic tinted	2.709

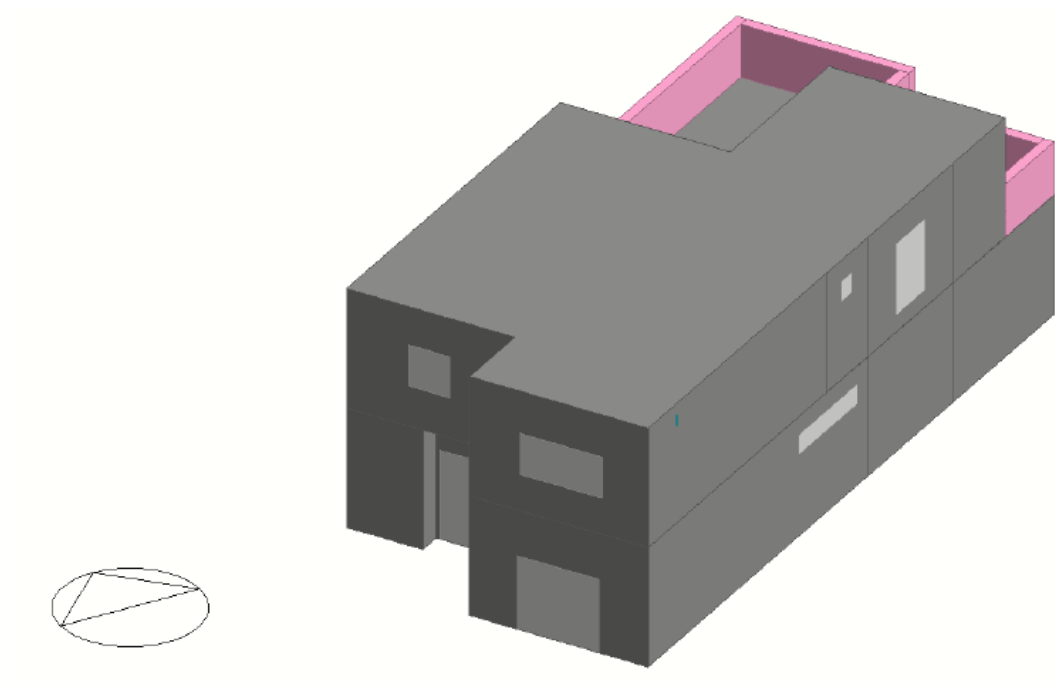
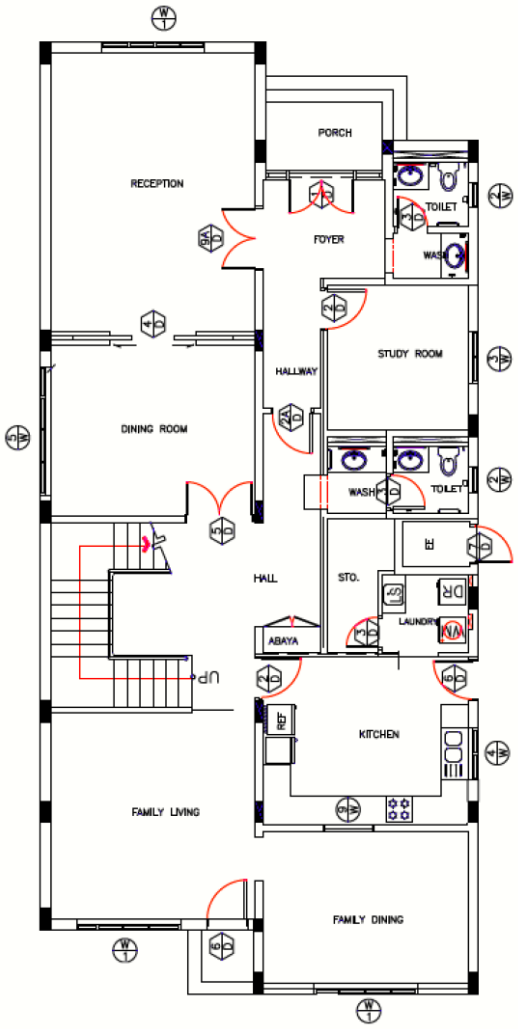


Figure 16: The extruded 3D model


RECEPTION
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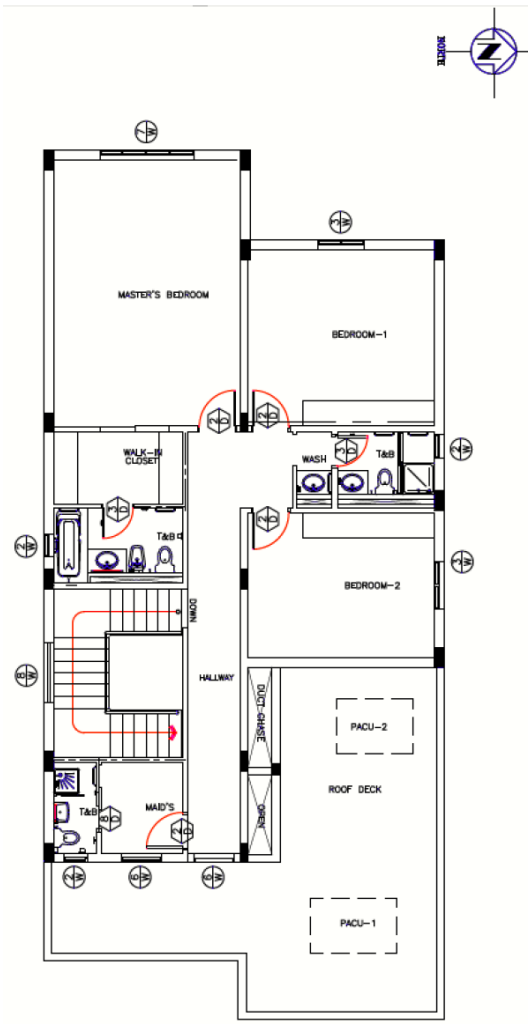
(a)


MASTER'S BEDROOM
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PACU-2
ROOF DECK
MAID'S
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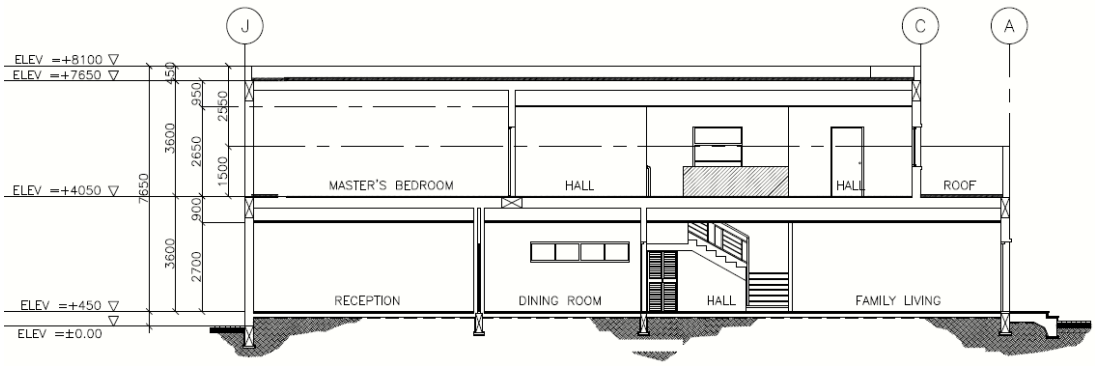

(d)

Figure 17: (a) Ground floor plan, (b) first-floor plan, (c) Front Elevation, (d) Section

4.2 Calibration

Model calibration is a critical step to ensure the simulation accurately reflects the performance of the existing building. This process involves running the model and validating its output against actual electricity utility bills. The calibration procedure follows the sequence outlined in Figure 18.

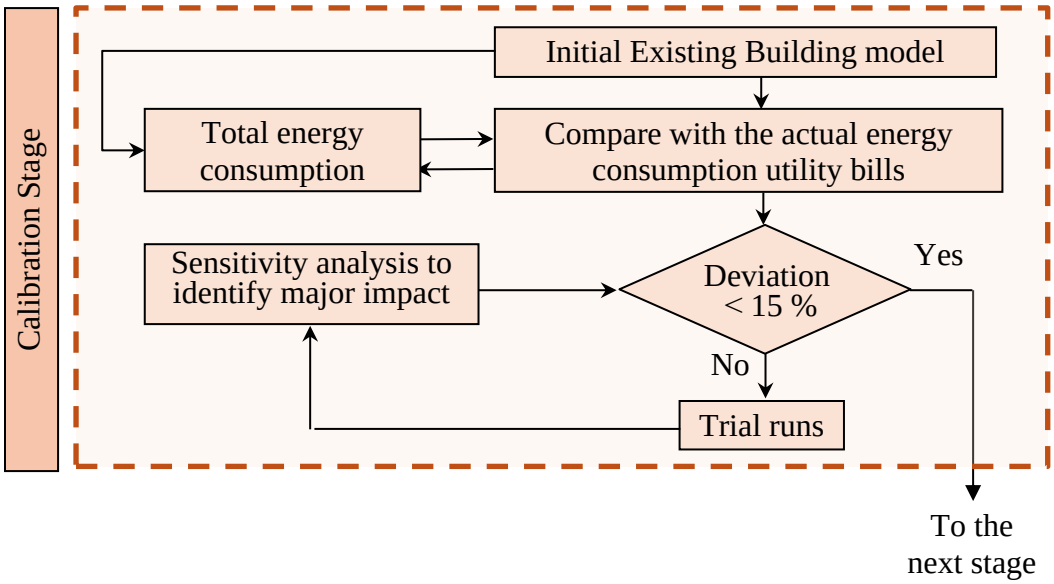

Figure 18: The Calibration Stage Flowchart

After applying the necessary adjustments to better align the simulation model with real-world conditions, the results showed a strong correlation with actual energy consumption data, with an overall deviation of 0.15%. This exceptional level of accuracy affirms the model's reliability, particularly in light of ASHRAE Guideline 14 [82], which considers a simulation model to be properly calibrated when the deviation from actual monthly utility data remains within 15%. Figure 19 illustrates the calibration curves in comparison with the measured energy consumption values.

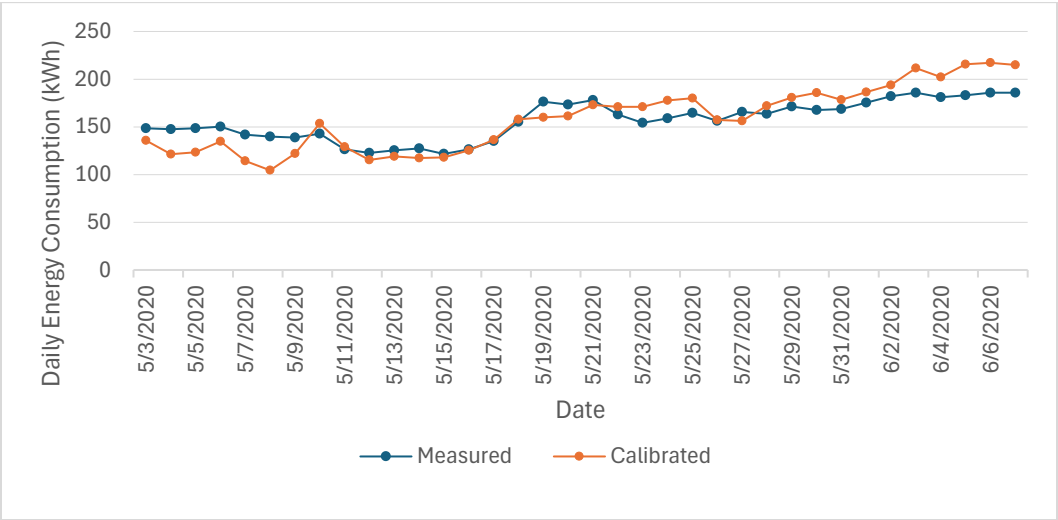

Figure 19: Comparison of daily cooling energy consumption between the simulation model and actual utility bills.

4.3 Scenarios Modeling

Once the model has been successfully calibrated, the scenario modeling stage begins. This stage is carried out according to the sequence shown in Figure 20.

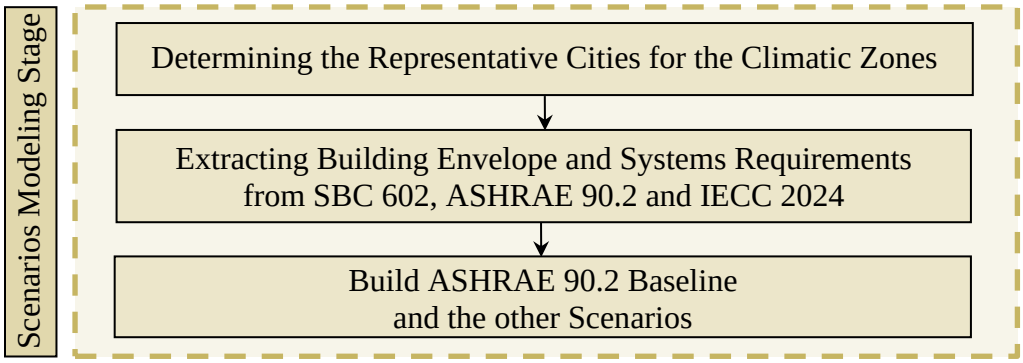

Figure 20: The Scenarios Modeling Stage Flowchart

4.3.1 Determining the Representative Cities for the Climatic Zones

Representative cities were selected to reflect the diverse climatic zones of Saudi Arabia, as outlined in section 2.4.4. Their corresponding climate classifications were then analyzed based on SBC 602, ASHRAE 169, and the IECC. This step is essential to determine the specific building envelope requirements for each city, as their classifications vary across standards. Table 11 summarizes the climatic zones for the eight selected cities according to these three frameworks, alongside the selected study from the literature.

Table 11: Climatic zones based on SBC 602, ASHRAE 169 and IECC for the eight cities

City	Climatic Zone in Literature [70]	Climatic Zone in SBC 602 [83]	Climatic Zone in ASHRAE Standard 169	Climatic Zone in IECC [84]
Riyadh	Extremely hot and dry	Zone 1	1B	Zone 1
Al-Wajh	Very hot and humid			
Taif	Very hot and dry	Zone 2	2B	Zone 2
Tabuk	Hot and dry			
Jizan	Extremely hot and humid (Highest EUI)	Zone 1	0B	Zone 0
Dhahran	Extremely hot and humid (Original City)			
Jeddah	Extremely hot and humid	Zone 1	0B	Zone 1
Abha	Hot and dry (Lowest EUI)	Zone 3	2B	Zone 3

4.3.2 Building Envelope and Systems Requirements

The requirements for the building envelope and HVAC systems, with a particular focus on the Coefficient of Performance (COP), were extracted from SBC 602, ASHRAE 90.2, and IECC. These parameters were used to construct the baseline model and develop various scenarios, which were subsequently evaluated using the Mostadam and LEED v4.1 for homes certification frameworks as benchmark standards.

To evaluate these scenarios under the Mostadam and LEED for homes rating systems, their respective assessment methodologies were followed. Mostadam requires determining baseline energy consumption based on ASHRAE 90.2 standards, while LEED for homes follows the Energy Star program, which mandates that the reference home complies with the IECC requirements. The SBC explicitly outlines the building envelope requirements, while for the minimum HVAC efficiency requirements, it references SASO 2663 [85].

Table 12 summarizes all the regulatory requirements for the various scenarios across the eight selected cities based on SBC 602 [80], ASHRAE 90.2 [83], and IECC.

Table 12: Regulatory requirements for all scenarios across the eight selected cities

City	Code	External Walls	Floor	Roof	External Windows		Air Tightness	HVAC
		U value W/(m2.K)				SHGC	ACH50	COP
Riyadh Al-Wajh	SBC 602	0.403	0.496	0.272	2.668	0.25	4.0	2.43
	ASHRAE Baseline	1.120	0.360	0.200	6.820	0.30	3.0	3.52
	IECC Home	0.197	0.064	0.035	0.500	0.25	2.5	3.52
Taif Tabuk	SBC 602	0.454	0.496	0.340	2.668	0.25	4.0	2.43
	ASHRAE Baseline	0.940	0.360	0.200	3.690	0.30	3.0	3.52
	IECC Home	0.165	0.064	0.030	0.400	0.25	2.5	3.52
Jizan Dhahran	SBC 602	0.403	0.496	0.272	2.668	0.25	4.0	2.43
	ASHRAE Baseline	1.120	0.360	0.200	6.820	0.30	3.0	3.52
	IECC Home	0.197	0.064	0.035	0.500	0.25	2.5	3.52
Jeddah	SBC 602	0.403	0.496	0.272	2.668	0.25	4.0	2.43
	ASHRAE Baseline	1.120	0.360	0.200	6.820	0.30	3.0	3.52
	IECC Home	0.197	0.064	0.035	0.500	0.25	2.5	3.52
Abha	SBC 602	0.511	0.496	0.397	2.668	0.25	4.0	2.43
	ASHRAE Baseline	0.940	0.360	0.200	3.690	0.30	3.0	3.52
	IECC Home	0.098	0.047	0.030	0.300	0.25	2.5	3.52

4.3.3 ASHRAE 90.2 Baseline and the Other Scenarios

The process began with the development of the Energy Star Reference Home model and the ASHRAE 90.2 baseline model, as no predefined templates for these were available in DesignBuilder. A total of eight models were created for each, corresponding to the eight selected cities. Subsequently, various scenarios were constructed, including models representing existing buildings and those compliant with the SBC across the same cities.

To develop the baseline building model for ASHRAE 90.2, the Energy Star Reference Home, the SBC-compliant models, modifications were made to the initial model (Case A). All models share several fundamental similarities as they utilized the same weather data

specific to the eight cities, ensuring consistency in addressing the unique climatic conditions and comfort zone properties of each location. Additionally, temperature and humidity control set-points, as well as operational schedules, were aligned with those defined in the initial case model. Furthermore, all models maintained identical geometry, total floor area, number of floors, and conditioned floor area to ensure comparability across simulations.

The key differences between the models lie in the building envelope characteristics and HVAC efficiency, especially COP, which were adjusted according to the requirements of each phase. Following the completion of the modeling process, simulations were conducted for all scenarios.

4.4 Simulation

This stage involves two sets of simulations, as illustrated in Figure 21. The first set focuses on assessing the effectiveness of the SgBC and SBC 602 in promoting sustainability across Saudi Arabia's diverse climatic zones, using the Mostadam and LEED v4.1 for homes frameworks as evaluation tools. A single building model (Case A) was simulated across eight different cities, and its energy performance was compared against models compliant with SBC 602, as well as baseline models based on ASHRAE 90.2 and IECC reference home standards. This comparative analysis demonstrates how regional climate variations influence the green building rating of an identical design when evaluated under different certification frameworks.

The second set of simulations aims to align the study with the current conditions of typical existing buildings outside of high-standard developments, such as those found on

the KFUPM campus. Given the unique characteristics and construction practices of each region, additional scenarios were developed to represent case studies of existing buildings in Dhahran, Riyadh, and Jeddah. This set assesses the SgBC and SBC's effectiveness in enhancing sustainability under diverse local jurisdictions and regulatory environments. The properties of these buildings were derived from existing literature [86] [87] [88], and are summarized in Table 13.

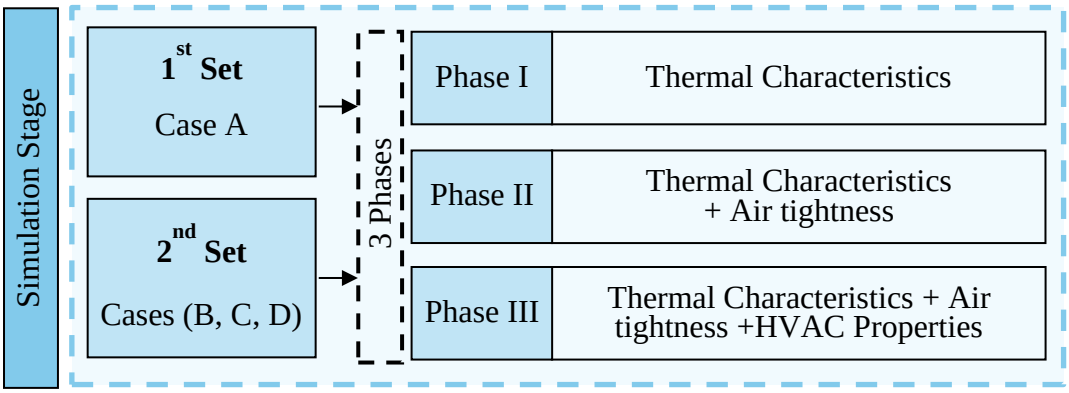

Figure 21: The Simulation Stage Flowchart

Table 13: The characteristics of the building cases of the second set of simulations

City	Code	External Walls	Floor	Roof	External Windows		Air Tightness	HVAC
		U value W/ (m2.K)				SHGC	ACH50	COP
Dhahran [81]	Case B	2.23	1.07	1.93	6.10	0.82	7.12	2.35
Jeddah [82]	Case C	2.70	1.90	2.80	5.57	0.86		
Riyadh [83]	Case D	1.30	1.70	2.30	5.60	0.86		

Each set of simulations was conducted in three distinct phases to systematically evaluate the impact of various parameters on energy consumption and CO_2 emissions and to assess the influence of each parameter in order to identify the most impactful factors, and pinpoint areas for improvement within SgBC. The first phase focused solely on the thermal characteristics across all scenarios in the eight selected cities. The second phase

expanded the analysis to include the entire building envelope, incorporating both thermal characteristics and airtightness. Finally, the third phase integrated the building envelope with the minimum efficiency requirements for HVAC systems, especially COP.

After the simulation, the energy results were analyzed. Several studies [87], [89], [90] have shown that approximately 70% of total energy consumption in residential buildings in Saudi Arabia is used for space cooling. The simulation models provided results only for the cooling systems because internal loads, such as occupants and equipment, were not included during the calibration process. Therefore, the simulation results represent 70% of the building's total energy use. To estimate the full energy consumption, an additional 30% was added to the results. This value was applied uniformly across all scenarios, as it remains constant in each case.

The energy results yielded three metrics for all scenarios: EUI (utilized in Mostadam O+E), zEPI (adopted in SgBC), and HERS Index (implemented in LEED v4.1 for homes), percentage of improvement (applied in Mostadam D+C) along with potential Mostadam and LEED certification points. To calculate the EUI, the energy consumption was divided by the conditioned area of the house as per Equation 5, while to calculate the zEPI, the building's performance in source kBtu was determined by multiplying its energy consumption by a conversion factor specific to the fuel type used. Subsequently, the zEPI was calculated using Equation 6, as specified in the Saudi Green Building Code (SgBC). SgBC mandates that the value of the zEPI shall not exceed 50. The improvement percentage, the points of Mostadam D+C and the points of Mostadam O+ E can be calculated as per section 2.4.3.

$$EUI = \frac{\text{Energy consumption}}{\text{Conditioned Area}} \qquad \text{Equation 5}$$

$$zEPI = 52 \text{ x } \frac{\text{Proposed Building Performance}}{\text{Baseline Building Performance}} \qquad \text{Equation 6}$$

4.5 Results Analysis

Following the simulations, each scenario's performance was evaluated based on CO_2 emissions and total energy consumption, as illustrated in Figure 22. In addition, multiple energy performance indicators, including EUI, zEPI, HERS, and percentage improvement, were analyzed to determine the most accurate and effective metric for assessing energy efficiency. The corresponding certification points for Mostadam D+C, Mostadam O+E, and LEED v4.1 for homes were calculated for all simulation phases, as presented in Tables 15, 16, 17, and 18.

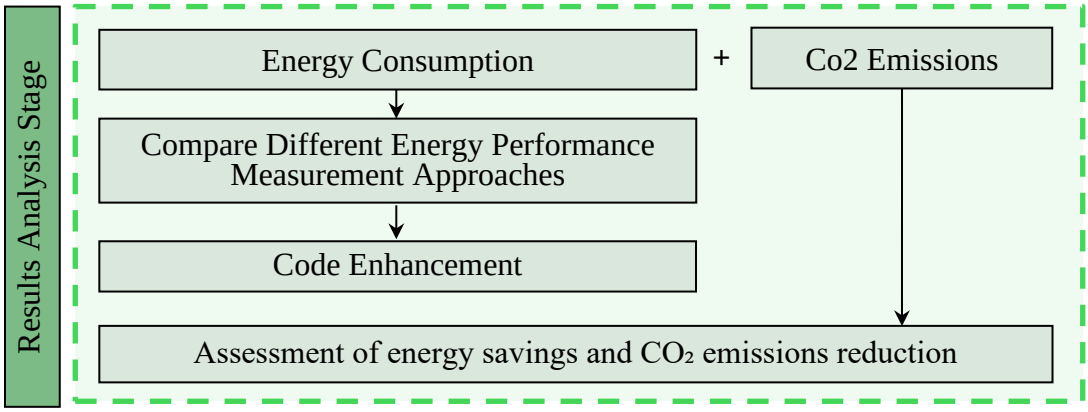

Figure 22: The Analysis Stage Flowchart

The final step involves code enhancement, where findings from the simulations are used to propose refinements to the Saudi building codes. The stage concludes with an

Assessment of energy savings and CO_2 emissions reduction, demonstrating the potential benefits of integrating best practices into national building regulations.

4.5.1 First Simulation Set

This section presents the results of the first set of simulations. The analysis is divided into three phases, each considering a distinct set of parameters as outlined in section 4.4.

4.5.1.1. Phase I

This phase focuses exclusively on the thermal characteristics of the building envelope. The simulation results for all scenarios within this phase are summarized in Table 14.

Table 14: Simulation results for Phase I of the 1st simulation set

City	Case	Energy Consumption (kWh)	zEPI	EUI (kWh/m²)	Mostadam O+E Rating	Mostadam Points O+E	Improvement (%)	Mostadam Points D+C	Adjusted HERS	Points
Riyadh	Case A	47300.97	46.29	164.83	B	3	11%	7	108.5	0
	SBC 602	46398.81	45.41	161.69	B	3	13%	7	106.4	0
	ASHRAE 90.2	53130.86	-	185.15	C	1	0%	5	121.9	0
	IECC Home	42539.98	-	148.24	A	5	20%	8	-	-
Al-Wajh	Case A	48373.92	46.48	168.57	B	3	11%	7	106.2	0
	SBC 602	47609.22	45.74	165.91	B	3	12%	7	104.6	0
	ASHRAE 90.2	54121.13	-	188.60	C	1	0%	5	118.9	0
	IECC Home	44426.90	-	154.82	B	3	18%	8	-	-
Taif	Case A	35405.77	49.05	123.38	A	5	6%	6	105.6	0
	SBC 602	35197.15	48.76	122.66	A	5	6%	6	104.9	0
	ASHRAE 90.2	37532.18	-	130.79	A	5	0%	5	111.9	0
	IECC Home	32728.00	-	114.05	A+	7	13%	7	-	-
Tabuk	Case A	40394.37	48.58	140.77	A	5	7%	6	108.0	0
	SBC 602	40165.45	48.30	139.97	A	5	7%	6	107.4	0
	ASHRAE 90.2	43241.21	-	150.69	B	3	0%	5	115.6	0
	IECC Home	36508.06	-	127.22	A	5	16%	8	-	-
Jizan	Case A	71736.58	45.44	249.99	D	0	13%	7	109.1	0
	SBC 602	70715.13	44.79	246.43	D	0	14%	7	107.5	0
	ASHRAE 90.2	82092.16	-	286.08	E	0	0%	5	124.8	0
	IECC	64180.68	-	223.66	C	1	22%	9	-	-
Dhahran	Case A	58739.92	45.64	204.70	C	1	12%	7	108.6	0
	SBC 602	57688.41	44.82	201.03	C	1	14%	7	106.6	0
	ASHRAE 90.2	66928.56	-	233.23	D	0	0%	5	123.7	0
	IECC Home	52791.34	-	183.97	B	3	21%	9	-	-
Jeddah	Case A	63602.51	45.68	221.64	C	1	12%	7	108.2	0
	SBC 602	62658.83	45.00	218.35	C	1	13%	7	106.6	0
	ASHRAE 90.2	72405.32	-	252.32	D	0	0%	5	123.2	0
	IECC Home	57333.05	-	199.79	C	1	21%	9	-	-
Abha	Case A	23493.19	51.21	81.87	A+	7	2%	5	101.0	0
	SBC 602	23361.47	50.93	81.41	A+	7	2%	5	100.4	0
	ASHRAE 90.2	23854.14	-	83.13	A+	7	0%	5	102.5	0
	IECC Home	22704.29	-	79.12	A+	7	5%	5	-	-

Based on the results, the following observations can be drawn:

1. The data reveals a clear hierarchy in energy performance standards:

   - IECC Home demonstrates superior performance across all cities, achieving 13-22% improvements over ASHRAE 90.2 baselines.

   - SBC consistently outperforms ASHRAE 90.2 baseline (6-14% improvements) while falling short of IECC benchmarks.

   - Existing building (Case A) generally exceeds ASHRAE 90.2 baseline requirements which means that it adheres to high standards but requires upgrades to meet SBC 602/IECC standards.

2. Climate-Driven Performance Variations:

   - Extreme climates demand stricter standards as coastal cities (Jizan, Jeddah) show 2-3× higher EUIs than mountainous Abha.

   - Cooling is the main driver of consumption, with Jizan's ASHRAE 90.2 baseline EUI of 286.08 indicating the highest cooling demand.

   - SBC 602 demonstrates climate adaptability, yielding 12–14% improvements in harsh climates compared to only 2–7% in temperate regions.

3. Certification & Compliance Insights:

- zEPI Performance:
  - SBC 602 model and Case A maintain sub-50 zEPI values across all cities except Abha.
  - The zEPI metric shows inconsistencies when compared to Mostadam ratings. For instance, some scenarios with zEPI values exceeding the recommended threshold of 50, such as Case A in Abha with a zEPI of 51.21, still achieve high Mostadam classifications (A+). In contrast, other scenarios with lower zEPI values, such as Case A in Jeddah (45.68) and Jizan (45.44), receive significantly lower ratings (C and D, respectively). This discrepancy suggests that Energy Use Intensity (EUI) plays a more influential role in Mostadam certification outcomes. Additionally, it indicates that climate-specific adjustments may significantly impact the final ratings, as illustrated in Figure 23.
- Mostadam Ratings:
  - ASHRAE 90.2 baselines typically meet minimum compliance (5 points)
  - IECC models consistently achieve A/A+ ratings (7-9 O+E points)
  - Mostadam D+C assessment consistently awards higher point values than the Mostadam O+E evaluation for equivalent cases.

- LEED V4.1 for homes

  - All evaluated scenarios including existing building cases, ASHRAE 90.2 baselines, and SBC-compliant models achieved HERS scores above 70, rendering them ineligible for points under LEED certification.

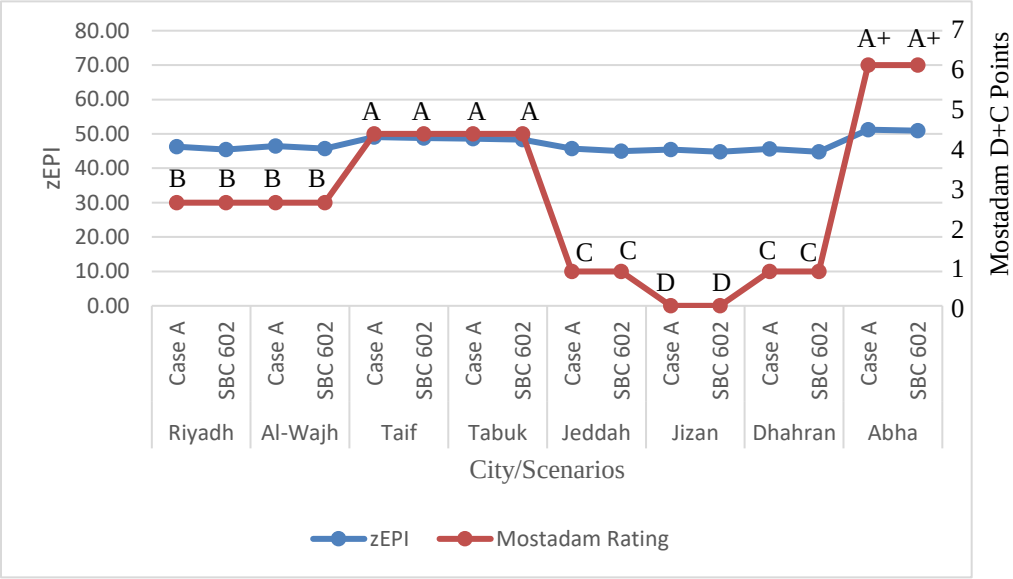

Figure 23: zEPI & Mostadam Rating for Phase I of the 1st simulation set

4.5.1.2. Phase II

This phase focuses on the complete building envelope requirements, thermal characteristics and airtightness. Table 15 presents a detailed summary of the results for Phase II of the first set of simulations across the eight cities.

Table 15: Simulation results for Phase II of the 1st simulation set

City	Case	Energy Consumption (kWh)	zEPI	EUI (kWh/m²)	Mostadam O+E Rating	Mostadam Points O+E	Improvement (%)	Mostadam Points D+C	Adjusted HERS	Points
Riyadh	Case A	47687	46.5	166.2	B	3	11%	7	108.7	0
	SBC 602	46712	45.5	162.8	B	3	12%	7	106.4	0
	ASHRAE 90.2	53371	-	186.0	C	1	0%	5	121.6	0
	IECC Home	42821	-	149.2	A	5	20%	8	-	-
Al-Wajh	Case A	48756	46.6	169.9	B	3	10%	7	106.4	0
	SBC 602	47921	45.8	167.0	B	3	12%	7	104.6	0
	ASHRAE 90.2	54357	-	189.4	C	1	0%	5	118.6	0
	IECC Home	44708	-	155.8	B	3	18%	8	-	-
Taif	Case A	35677	49.2	124.3	A	5	5%	6	105.7	0
	SBC 602	35425	48.8	123.4	A	5	6%	6	104.9	0
	ASHRAE 90.2	37730	-	131.5	A	5	0%	5	111.7	0
	IECC Home	32946	-	114.8	A+	7	13%	7	-	-
Tabuk	Case A	40708	48.7	141.9	A	5	6%	6	108.1	0
	SBC 602	40422	48.4	140.9	A	5	7%	6	107.3	0
	ASHRAE 90.2	43458	-	151.4	B	3	0%	5	115.4	0
	IECC Home	36753	-	128.1	A	5	15%	8	-	-
Jizan	Case A	72369	45.5	252.2	D	0	12%	7	109.3	0
	SBC 602	71200	44.8	248.1	D	0	14%	7	107.5	0
	ASHRAE 90.2	82696	-	288.2	E	0	0%	5	124.9	0
	IECC Home	64598	-	225.1	D	0	22%	9	-	-
Dhahran	Case A	59204	45.8	206.3	C	1	12%	7	108.8	0
	SBC 602	58055	44.9	202.3	C	1	14%	7	0.0	0
	ASHRAE 90.2	67194	-	234.2	D	0	0%	5	123.4	0
	IECC Home	53115	-	185.1	C	1	21%	9	-	-
Jeddah	Case A	64141	45.9	223.5	C	1	12%	7	108.5	0
	SBC 602	63079	45.1	219.8	C	1	13%	7	106.7	0
	ASHRAE 90.2	72705	-	253.4	D	0	0%	5	122.9	0
	IECC Home	57700	-	201.1	C	1	21%	9	-	-
Abha	Case A	23656	51.2	82.4	A+	7	1%	5	101.0	0
	SBC 602	23518	50.9	82.0	A+	7	2%	5	100.4	0
	ASHRAE 90.2	24006	-	83.7	A+	7	0%	5	102.5	0
	IECC Home	22862	-	79.7	A+	7	5%	5	-	-

The simulation results reveal several important observations:

- The results show minimal deviation (<1% variation in EUI/energy consumption) compared to Phase I (thermal-only) outcomes.
- IECC reference home remains the top performer in all cities.
- Identical Mostadam O+E/D+C point allocations in phases.
- All scenarios maintain their original Mostadam classifications.
- All HERS scores persistently exceed the LEED certification threshold of 70.
- SBC 602 consistently outperforms ASHRAE 90.2 in meeting comprehensive building envelope requirements.

The negligible performance variation between the two phases indicates that thermal characteristics predominantly determine energy efficiency in Saudi Arabia's climate conditions, while airtightness demonstrates a comparatively minor influence.

4.5.1.3. Phase III

This phase focuses on the full building envelope requirements, including thermal properties and airtightness, as well as HVAC system characteristics, with particular attention to COP. Table 16 presents a detailed summary of the results for Phase III of the first set of simulations across the eight cities.

Table 16: Simulation results for Phase III of the 1st simulation set

City	Case	Energy Consumption (kWh)	zEPI	EUI (kWh/m²)	Mostadam O+E Rating	Mostadam Points O+E	Improvement (%)	Mostadam Points D+C	Adjusted HERS	Points
Riyadh	Case A	47687	60.6	166.2	B	3	-16%	0	134.3	0
	SBC 602	45094	57.3	157.1	B	3	-10%	0	127.0	0
	ASHRAE 90.2	40944	-	142.7	A	5	0%	5	115.3	0
	IECC Home	34658	-	120.8	A	5	15%	8	-	-
Al-Wajh	Case A	48756	61.0	169.9	B	3	-17%	0	132.4	0
	SBC 602	46248	57.8	161.2	B	3	-11%	0	125.6	0
	ASHRAE 90.2	41595	-	144.9	A	5	0%	5	113.0	0
	IECC Home	35931	-	125.2	A	5	14%	7	-	-
Taif	Case A	35677	60.3	124.3	A	5	-16%	0	124.3	0
	SBC 602	39167	66.2	136.5	A	5	-27%	0	136.5	0
	ASHRAE 90.2	30773	-	107.2	A+	7	0%	5	107.2	0
	IECC Home	28001	-	97.6	A+	7	9%	6	-	-
Tabuk	Case A	40708	61.4	141.9	A	5	-18%	0	129.9	0
	SBC 602	39167	59.0	136.5	A	5	-14%	0	125.0	0
	ASHRAE 90.2	34500	-	120.2	A	5	0%	5	110.1	0
	IECC Home	30567	-	106.5	A+	7	11%	7	-	-
Jizan	Case A	72369	61.9	252.2	D	0	-19%	0	143.1	0
	SBC 602	68205	58.3	237.7	D	0	-12%	0	134.9	0
	ASHRAE 90.2	60813	-	211.9	C	1	0%	5	120.3	0
	IECC Home	49342	-	171.9	B	3	19%	8	-	-
Dhahran	Case A	59204	61.6	206.3	C	1	-18%	0	138.8	0
	SBC 602	55861	58.1	194.7	C	1	-12%	0	112.6	0
	ASHRAE 90.2	49997	-	174.2	B	3	0%	5	117.2	0
	IECC Home	41609	-	145.0	A	5	17%	8	-	-
Jeddah	Case A	64141	62.3	223.5	C	1	-20%	0	140.0	0
	SBC 602	60547	58.8	211.0	C	1	-13%	0	132.2	0
	ASHRAE 90.2	53535	-	186.6	C	1	0%	5	116.9	0
	IECC Home	44691	-	155.7	B	3	17%	8	-	-
Abha	Case A	23656	56.3	82.4	A+	7	-8%	0	108.9	0
	SBC 602	23213	55.3	80.9	A+	7	-6%	0	106.8	0
	ASHRAE 90.2	21835	-	76.1	A+	7	0%	5	100.5	0
	IECC Home	21201	-	73.9	A+	7	3%	5	-	-

The analysis of the results of this phase of simulation reveals three fundamental shifts from previous phases:

1. **HVAC Dominance Effect**

   - COP requirements reversed previous performance trends, with ASHRAE 90.2 baseline now outperforming SBC 602 in 6 out of 8 cities.
   - IECC reference home's advantage was reduced from 20% (Phase II) to an average 15% improvement.
   - Existing building cases (Case A) showed negative performance (-6% to -20% vs ASHRAE 90.2 baseline) after it was positive in the previous two phases.
   - HVAC system selection now outweighs envelope optimization (70% of variance in Phase III results).

2. **Climate-Specific Impacts**

   - Hot-Humid Climates (Jizan/Jeddah):
     - 30-50 points HERS score increases versus Phase II.
     - Mostadam ratings downgraded 40% of scenarios.
   - Moderate Climates (Riyadh/Tabuk):
     - 10-15% reduction in improvement percentages.

- Cool Climates (Abha/Taif):
    - Minimal variation (≤5%) from Phase II results.

3. **Certification Implications**

- 57% of scenarios lost Mostadam D+C points compared to Phase II.
- The simulation results demonstrate that all SBC 602-compliant scenarios achieved sustainable performance levels according to Mostadam O+E criteria, with the sole exception of Jizan as illustrated in Figure 24.
- There remains an inconsistency between the zEPI values and the Mostadam rating, as the zEPI value exceeds 50 while the rating remains high, as illustrated in the Figure 25.
- All HERS scores moved further from LEED v4.1 threshold (average +25 points).
- LEED's HERS 70 threshold becomes increasingly challenging.

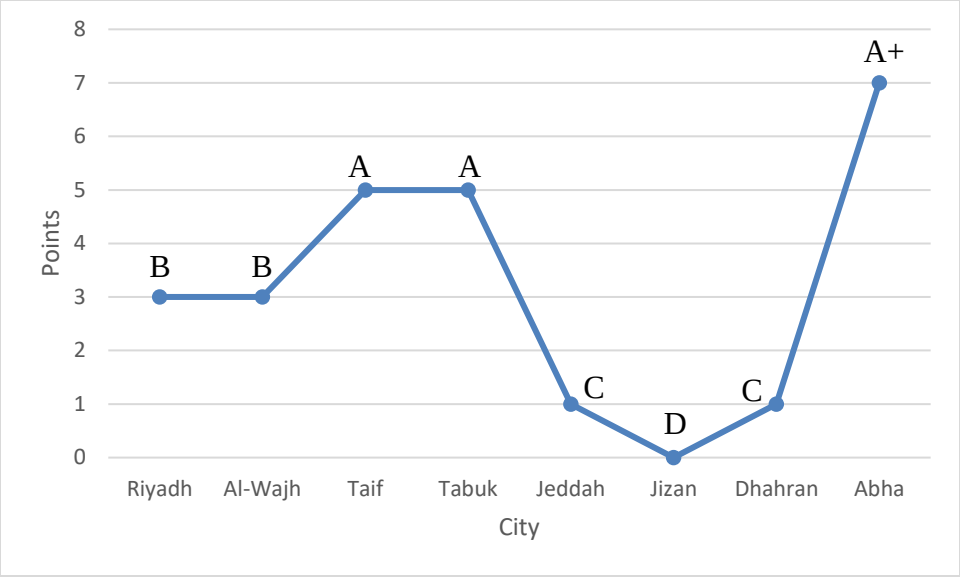

Figure 24: Mostadam Rating for SBC 602 Scenarios for phase III of the 1st set

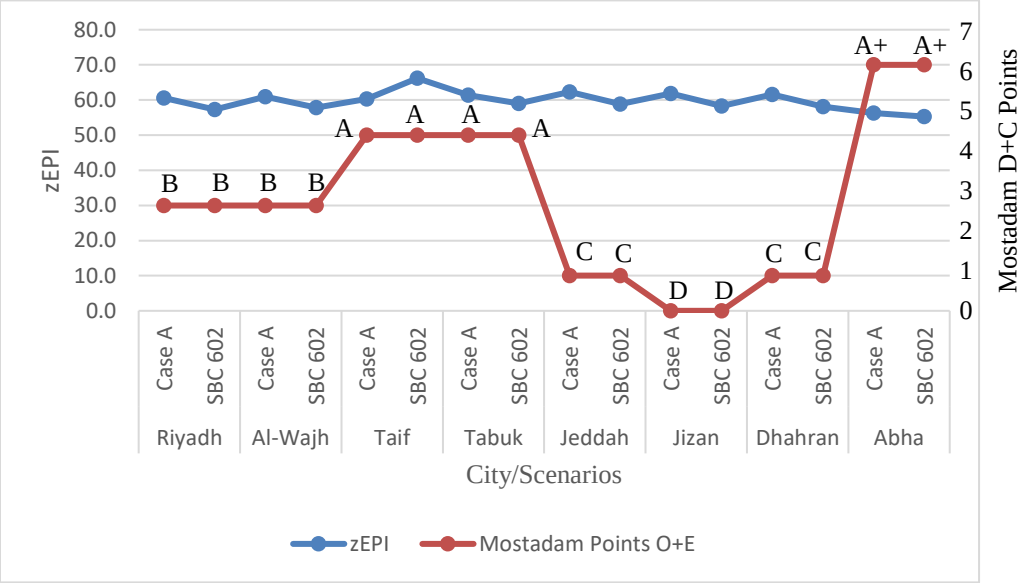

Figure 25: zEPI and Mostadam Rating for phase III of the 1st set

4.5.2 Second Simulation Set

This section presents the results from the second simulation set, organized into three phases. Each phase addresses a specific group of parameters, as detailed in section 4.4.

4.5.2.1. Phase I

This phase focuses exclusively on the thermal characteristics of the building envelope. The simulation results for all scenarios within this phase are summarized in Table 17.

Table 17: Simulation results for Phase I of the 2nd simulation set

City	Case	Energy Consumption (kWh)	zEPI	EUI (kWh/m^2)	Mostadam O+E Rating	Mostadam Points O+E	Improvement (%)	Mostadam Points D+C	Adjusted HERS	Points
Riyadh	Case D	56388.57	55.19	196.50	C	1	-6%	0	129.3	0
	SBC 602	46398.81	45.41	161.69	B	3	13%	7	106.4	0
	ASHRAE 90.2	53130.86	-	185.15	C	1	0%	5	121.9	0
	IECC Home	42539.98	-	148.24	A	5	20%	8	-	-
Dhahran	Case B	76765.24	59.64	267.51	E	0	-15%	0	141.9	0
	SBC 602	57688.41	44.82	201.03	C	1	14%	7	106.6	0
	ASHRAE 90.2	66928.56	-	233.23	D	0	0%	5	123.7	0
	IECC Home	52791.34	-	183.97	B	3	21%	9	-	-
Jeddah	Case C	85746.46	61.58	298.81	E	0	-18%	0	145.9	0
	SBC 602	62658.83	45.00	218.35	C	1	13%	7	106.6	0
	ASHRAE 90.2	72405.32	-	252.32	D	0	0%	5	123.2	0
	IECC Home	57333.05	-	199.79	C	1	21%	9	-	-

Based on the results from **Phase I** of the **second simulation set**, the following key observations can be made:

1. Poor performers (Cases B, C and D) show negative improvements (-6% to -18%) and E ratings, highlighting critical inefficiencies, validating the need for applying advanced codes.

2. SBC 602 scenarios maintain sub-50 zEPI values while Case B, Case C and Case D exceed 50 zEPI.

3. IECC reference home consistently delivers the best performance, achieving the highest improvement percentages (20–21%) comparing to ASHRAE 90.2 baseline and earning the most Mostadam D+C points (8–9).

4. Adjusted HERS scores are high (above 100) for all scenarios, indicating that none of the cases qualify for LEED v4.1 for homes certification.

5. Mostadam O+E ratings vary significantly across scenarios, with most cases receiving C or D, and E ratings in existing building cases for Dhahran and Jeddah, suggesting poor operational efficiency without improvements.

6. Although some scenarios, such as Riyadh, have higher zEPI values than others like Jeddah, they still achieve better Mostadam ratings (B for Riyadh vs. C for Jeddah). This suggests that EUI significantly influences certification outcomes, and climate-specific factors may impact the final ratings, as illustrated in Figure 26.

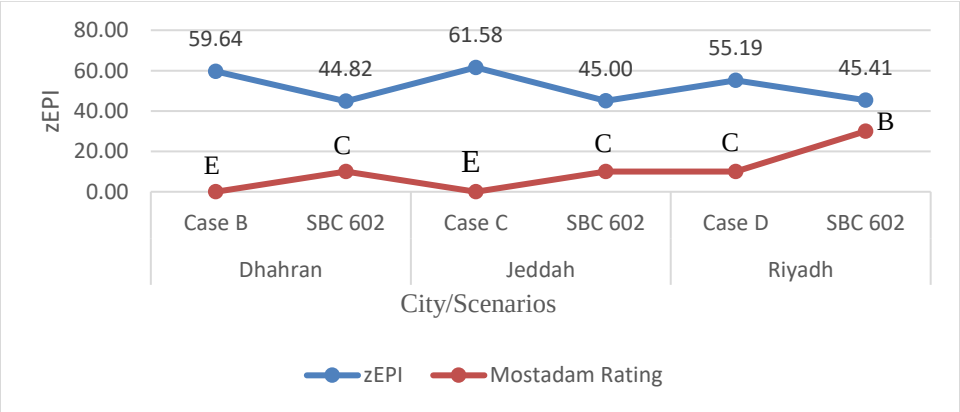

Figure 26: zEPI & Mostadam Rating for Phase I of the 2nd simulation set

4.5.2.2. Phase II

This phase focuses on the complete building envelope requirements, thermal characteristics, and airtightness. Table 18 presents a detailed summary of the results for Phase II of the second set of simulations across the eight cities.

Table 18: Simulation results for Phase II of the 2nd simulation set

City	Case	Energy Consumption (kWh)	zEPI	EUI (kWh/m^2)	Mostadam O+E Rating	Mostadam Points O+E	Improvement (%)	Mostadam Points D+C	Adjusted HERS	Points
Riyadh	Case D	56630	55.2	197.3	C	1	-6%	0	129.0	0
	SBC 602	46712	45.5	162.8	B	3	12%	7	106.4	0
	ASHRAE 90.2	53371	-	186.0	C	1	0%	5	121.6	0
	IECC Home	42821	-	149.2	A	5	20%	8	-	-
Dhahran	Case B	77049	59.6	268.5	E	0	-15%	0	141.6	0
	SBC 602	58055	44.9	202.3	C	1	14%	7	0.0	0
	ASHRAE 90.2	67194	-	234.2	D	0	0%	5	123.4	0
	IECC Home	53115	-	185.1	C	1	21%	9	-	-
Jeddah	Case C	85989	61.5	299.7	E	0	-18%	0	145.4	0
	SBC 602	63079	45.1	219.8	C	1	13%	7	106.7	0
	ASHRAE 90.2	72705	-	253.4	D	0	0%	5	122.9	0
	IECC Home	57700	-	201.1	C	1	21%	9	-	-

The simulation results reveal several important observations:

- The results of phase II of the 2nd set of simulations (thermal + airtightness) show minimal deviation (<1% variation in EUI/energy consumption) from phase I of the 2nd set (thermal-only) outcomes.
- Case C and Case B maintain their status as the worst performers.
- All scenarios retain their initial Mostadam classifications.
- HERS scores consistently remain above LEED certification threshold of 70.

Both second phases of the two simulation sets lead to the same conclusion: under Saudi Arabia's climatic conditions, thermal envelope characteristics are the primary drivers of energy efficiency, whereas airtightness has a comparatively minor impact. This is supported by the minimal performance differences observed between the two phases.

4.5.2.3. Phase III

This phase focuses on the full building envelope requirements, including thermal properties and airtightness, as well as HVAC system characteristics, with particular attention to COP. Table 19 presents a detailed summary of the results for Phase III of the second set of simulations across the eight cities.

Table 19: Simulation results for Phase III of the 2nd simulation set

City	Case	Energy Consumption (kWh)	zEPI	EUI (kWh/m^2)	Mostadam O+E Rating	Mostadam Points O+E	Improvement (%)	Mostadam Points D+C	Adjusted HERS	Points
Riyadh	Case D	56630	71.9	197.3	C	1	-38%	0	159.4	0
	SBC 602	45094	57.3	157.1	B	3	-10%	0	127.0	0
	ASHRAE 90.2	40944	-	142.7	A	5	0%	5	115.3	0
	IECC Home	34658	-	120.8	A	5	15%	8	-	-
Dhahran	Case B	77049	80.1	268.5	E	0	-54%	0	180.7	0
	SBC 602	55861	58.1	194.7	C	1	-12%	0	112.6	0
	ASHRAE 90.2	49997	-	174.2	B	3	0%	5	117.2	0
	IECC Home	41609	-	145.0	A	5	17%	8	-	-
Jeddah	Case C	85989	83.5	299.7	E	0	-61%	0	187.7	0
	SBC 602	60547	58.8	211.0	C	1	-13%	0	132.2	0
	ASHRAE 90.2	53535	-	186.6	C	1	0%	5	116.9	0
	IECC Home	44691	-	155.7	B	3	17%	8	-	-

The analysis of the results of this phase of simulation highlights important outcomes:

1. The existing buildings (Case B, C, D) reflect the poorest performance, with the highest energy consumption, EUI, and zEPI values, receiving E ratings and zero

points in all Mostadam categories, underscoring the inefficiency of typical existing construction practices.

2. HERS scores remain above 100 in all scenarios, indicating that none of the models meet LEED criteria. The existing buildings (Case B, C, D) exhibit particularly high HERS values (e.g., 187.7 in Jeddah), reinforcing their poor energy performance.

To conclude, while SBC 602 improves upon the existing cases, it falls short of matching ASHRAE 90.2 baseline or IECC reference home in overall energy performance and certification outcomes.

4.5.3 Code Enhancement

As observed from Table 16 and Table 19 in phase III, all scenarios exceed a zEPI of 50, even when complying with SBC 602. This indicates that additional requirements and enhancements are necessary within SBC 602 to ensure buildings remain below the zEPI threshold. SBC 602 should consider dynamic COP requirements by climate zone as the COP clearly has the most significant impact on energy consumption.

To achieve this, the process should be reversed by first setting the zEPI target value at 50, then determining the corresponding total energy consumption that yields this score. By subtracting the previously added 30% (which accounts for occupant and equipment loads), the cooling energy consumption can be isolated. This is crucial, as the COP influences only the cooling load and does not affect the energy used by occupants or equipment.

Once the new value of cooling energy consumption is determined, Equation 10 will be applied to calculate the revised Coefficient of Performance (COP) required to ensure that

the zEPI does not exceed 50, as outlined in Table 20. This equation was derived based on the following steps:

$$\text{Cooling Electricity Consumption} = \frac{\text{Cooling Load}}{\text{COP}} \qquad \text{Equation 7}$$

Since the cooling load remains constant, the relationship between the initial and revised COP values can be expressed as follows:

$$\frac{\text{Cooling Load}}{\text{Initial COP}} = \text{Initial Cooling Consumption} \qquad \text{Equation 8}$$

$$\frac{\text{Cooling Load}}{\text{New COP}} = \text{New Cooling Consumption} \qquad \text{Equation 9}$$

By dividing the two equations, Equation 10 has been obtained.

$$\text{COP new} = \text{COP old} \times \frac{\text{New Cooling Consumption}}{\text{Old Cooling Consumption}} \qquad \text{Equation 10}$$

Table 20: Adjusted minimum COP values for representative cities across Saudi Arabia's climatic zones

Representative City	Cooling Consumption when zEPI =50	Updated COP
Riyadh	21608.4	3.07
Al-Wajh	22233.5	3.11
Taif	11827.7	4.40
Tabuk	15412.2	3.37
Jizan	40712.7	3.01
Dhahran	30313.2	3.05
Jeddah	33714.8	3.08
Abha	3234.3	4.10

The simulation was re-executed using adjusted COP values that were 0.01 higher than the previously calculated values, with the updated results presented in Table 21.

Table 21: The results of using the adjusted COP values

City	Adjusted COP	Energy Consumption (kWh)	zEPI	EUI (kWh/m^2)	Mostadam O+E Rating	Mostadam Points O+E	Improvement (%)	Mostadam Points D+C	Adjusted HERS	Points
Riyadh	3.08	39326	49.9	137.0	A	5	4%	5	92.2	0
Al-Wajh	3.12	39948	49.9	139.2	A	5	4%	5	93.7	0
Taif	4.41	29556	49.9	103.0	A+	7	4%	5	69.9	11
Tabuk	3.38	33150	50.0	115.5	A+	7	4%	5	78.4	0
Jizan	3.02	58350	49.9	203.3	C	1	4%	5	115.4	0
Dhahran	3.06	48017	49.9	167.3	B	3	4%	5	112.6	0
Jeddah	3.09	51408	49.9	179.1	B	3	4%	5	112.2	0
Abha	4.11	20984	50.0	73.1	A+	7	4%	5	50.4	26

As shown in Table 21 , applying the adjusted COP values successfully satisfies the zEPI target, bringing all values below 50 and achieving approximately a 4% improvement compared to the ASHRAE baseline. This resulted in earning 5 points under the Mostadam D+C framework. According to Mostadam O+E, all models across the selected cities achieved a rating of C or higher, which represents the minimum sustainability level required to earn points. In contrast, only two cities met the LEED v4.1 for homes threshold by achieving HERS values below 70. This indicates that the minimum sustainability requirement in LEED is significantly more stringent than that of Mostadam.

Although all scenarios consistently achieved a 4% improvement in performance compared to ASHRAE 90.2 baseline, they received varying sustainability ratings, raising questions about the fairness and consistency of the evaluation criteria. To address this, a new threshold ranking was established for each climatic zone, based on the EUI required

to attain a zEPI below 50. This ranking defines the minimum performance standard necessary for compliance, as detailed in Table 21.

4.5.4 CO_2 Emission Results

To assess CO_2 emissions, simulation results from each set were compiled and illustrated across three figures (Figure 27, Figure 28 and Figure 29). Figure 27 compares the various scenarios in the first simulation set, across its three phases, in terms of percentage improvement over the ASHRAE 90.2 baseline in eight cities. This comparison offers a clear overview of how different strategies affect CO_2 emissions and their alignment with broader sustainability objectives.

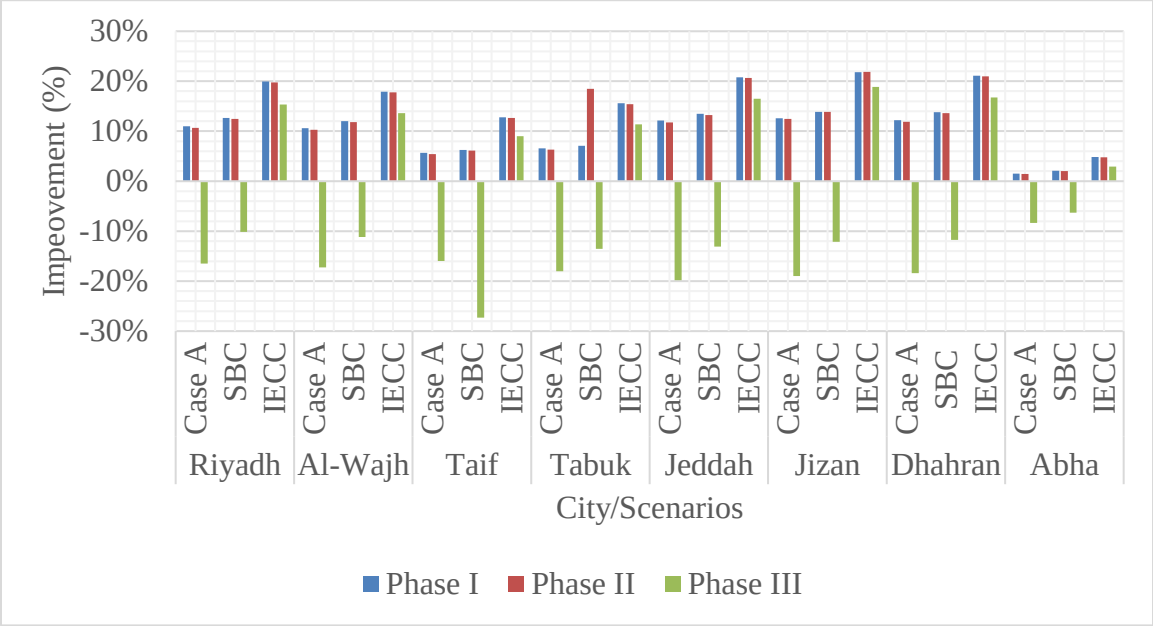

Figure 27: CO_2 Emissions – Percentage Improvement Over ASHRAE 90.2 Baseline Across All Scenarios (1st Simulation Set)

This figure reveals key observations that can be summarized as follows:

- Coastal cities (Jeddah, Jizan) show the highest absolute emissions, while mountainous Abha demonstrates the lowest emissions across all phases.
- Most cases show positive improvements in Phases I - II (typically 11-22%), but surprisingly negative improvements in Phase III.
- IECC standards deliver the most significant improvements (15-22% in Phases I - II, 9-19% in Phase III).

Figure 28 presents a comparison of CO_2 emissions for the existing building cases in the second simulation set across its three phases, based on the percentage improvement over the ASHRAE 90.2 baseline.

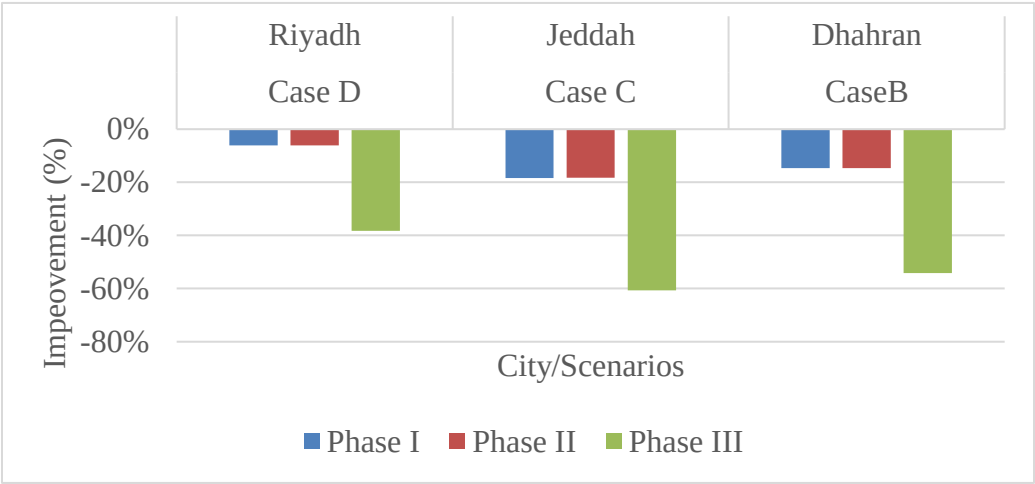

Figure 28: CO_2 Emissions – Percentage Improvement Over ASHRAE 90.2 Baseline for the existing building cases (2nd Simulation Set)

This figure shows that the existing building cases (Case D in Riyadh, Cases B-C in Dhahran/Jeddah) show negative improvements in all phases (-6% to -18% in Phases I - II, worsening to -38% to -61% in Phase III). This indicates that Phase III scenarios perform worse in terms of CO_2 emissions than the ASHRAE 90.2 baseline, highlighting a major efficiency shortfall. Figure 29 compares CO_2 emissions between scenarios following the current SBC 602 requirements and those incorporating the adjusted SBC 602, based on the percentage improvement over the ASHRAE 90.2 baseline including phase III parameters across the eight representative cities.

Figure 29: CO_2 Emissions – Percentage Improvement Over ASHRAE 90.2 Baseline for Current vs. Adjusted SBC 602

Figure 29 shows that the adjusted SBC 602 scenarios consistently achieve a modest 4% improvement in Phase III across all eight cities, demonstrating the positive impact of the code modifications. These results underscore the complex interplay between building standards, geographic context, and the stage of implementation in meeting CO_2 reduction goals.

4.5.5 Assessment of Energy Savings and CO_2 Emissions Reduction

This section presents an in-depth evaluation of energy consumption and CO_2 emissions reductions in new residential buildings, using simulation-based comparisons to assess the potential impact of implementing the current and adjusted versions of SBC 602.

Simulation results across eight representative cities were analyzed to quantify energy performance improvements relative to existing conditions. The consolidated outcomes are presented in Table 22. To estimate the national impact, data from the General Authority of Statistics (GASTAT) [79] was used to determine the annual construction rate for this residential building type, based on permit issuance. This served as a basis for projecting total energy and emissions savings on a national scale.

Using construction permit data from GASTAT as a proxy for annual construction rates of this residential building type, the total energy and emissions savings were projected for all new buildings of this category. The financial value of these energy savings was calculated based on Saudi Arabia's residential electricity tariffs, as regulated by the Electricity & Cogeneration Regulatory Authority (ECRA). The tariff structure follows a two-tier system [91]:

- 18 halalas/kWh for monthly consumption below 6,000 kWh.
- 30 halalas/kWh for consumption exceeding 6,000 kWh.

Given that the average consumption for this building type remains under 6,000 kWh for approximately 10 months per year, the lower rate of 18 halalas/kWh was applied to estimate financial savings.

Table 22: Assessment of Energy Savings and CO_2 Emissions Reduction in New Residential Buildings

New Buildings		
	Current SBC 602	Adjusted SBC 602
Average energy consumption (Existing Buildings) (kWh)	55624	
Average consumption saved (kWh)	6624	13852
Average CO_2 emissions (Existing Buildings) (Kg)	38492	
Average CO_2 saved (Kg)	4584	9586
Permits (Rate)	13161	
Total Consumption saved in 1 year (kWh)	87179122	182309595
Total CO_2 emissions saved in 1 year (Kg)	60327952	126158240
Electricity Tariff (SAR)	0.18	
Cost saved (SAR)	156922420	328157271

The analysis highlights the substantial advantages of implementing the current SBC 602, resulting in cost savings of 156,922,420 SAR. In addition to the financial benefits, the environmental impact is also significant. The adjusted SBC 602 achieves a 13% improvement in energy efficiency over the current code. Collectively, these enhancements could lead to energy savings of up to 182 million kWh and a reduction of 126 million kilograms of CO_2 emissions.

Figure 30 illustrates the savings percentage achieved by the current and adjusted SBC 602 compared to the performance of existing buildings. While the current SBC 602 achieves savings of up to 11.9%, the adjusted version reaches 24.9%, clearly demonstrating the enhanced effectiveness of the proposed modifications.

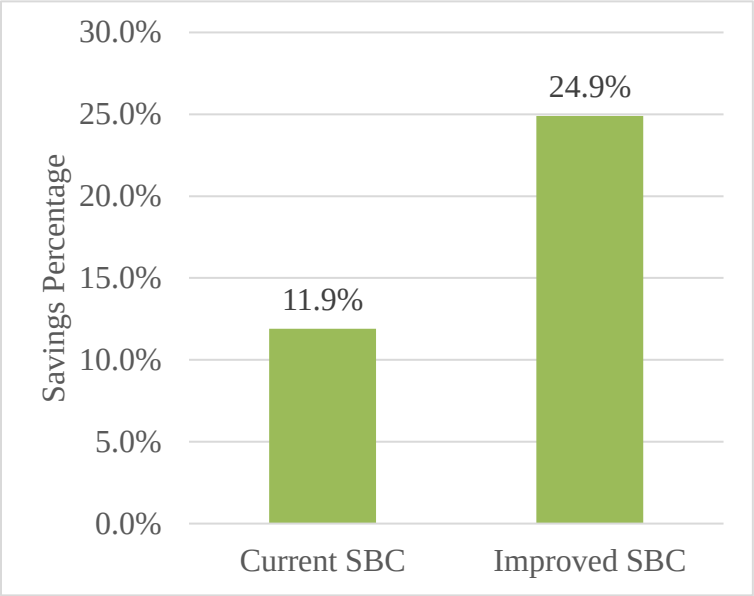

Figure 30: Savings Percentage of Current vs. Adjusted SBC 602 Compared to Existing Building Performance

CHAPTER 5

FRAMEWORK DEVELOPMENT

Research on the incorporation of green building principles into regulatory frameworks has shown promising results, including enhanced environmental performance, decreased operational expenses, and improved occupant health and well-being [5].

The energy category, due to its high impact and priority in reducing greenhouse gas emissions and improving building performance, serves as a particularly relevant focus for such integration. This framework outlines a systematic approach to achieve effective integration, using the energy category as a case study.

Based on observations from numerous studies discussing the integration of green building rating systems into local building codes, a common pattern emerges in the progression of sustainable building regulations. In most cases, the normal progression follows a structured order: a local building code is established first, providing the mandatory minimum requirements for construction. A green building rating system (GBRS) is then introduced as a voluntary or performance-based framework to encourage and assess sustainability beyond code compliance. The purpose of integrating a GBRS into a local building code is to enhance the regulatory framework by embedding sustainability practices that help achieve a minimum level of environmental performance when assessed under the rating system. However, in the case of Saudi Arabia (KSA), this process took a reverse approach. The Saudi Green Building Code (SgBC) was introduced before the

development of the country's official green building rating system, Mostadam [45]. Interestingly, Mostadam was built upon the foundations of SgBC 1001, rather than being an independent system introduced afterward to complement an existing code.

Given this unique context, the framework for integration in this study will follow the conventional sequence, first aligning the Saudi Building Code (SBC 602) with the sustainability practices outlined in Mostadam, to establish a more robust and sustainability-driven regulatory structure. The results of this integration will then be compared against the existing Saudi Green Building Code (SgBC) to determine how well the integrated system aligns with the Keystone Credits (mandatory sustainability benchmarks) and Additional Credits (optional enhancements) within Mostadam. This will allow for an evaluation of whether the proposed framework meets or exceeds the minimum sustainability thresholds set by the current Saudi green building framework.

By adopting this approach, this chapter synthesizes the findings from previous chapters into a step-by-step framework that can be applied to:

1. Enhance Saudi Arabia’s SgBC (as demonstrated in this study).

2. Integrate other green rating systems (e.g., LEED) into different local building codes worldwide.

3. Guide future research on improving energy efficiency standards in building regulations.

The framework is organized into four key sections: Inputs, Core Activities, Criteria, and Outputs, providing a systematic process for code improvement and policy integration.

The core activities follow a four-phase structure, adapted from the methodology employed in this thesis and generalized for wider applicability. Each phase includes specific steps. Figure 31 presents a flowchart of the proposed framework, visually detailing all its components.

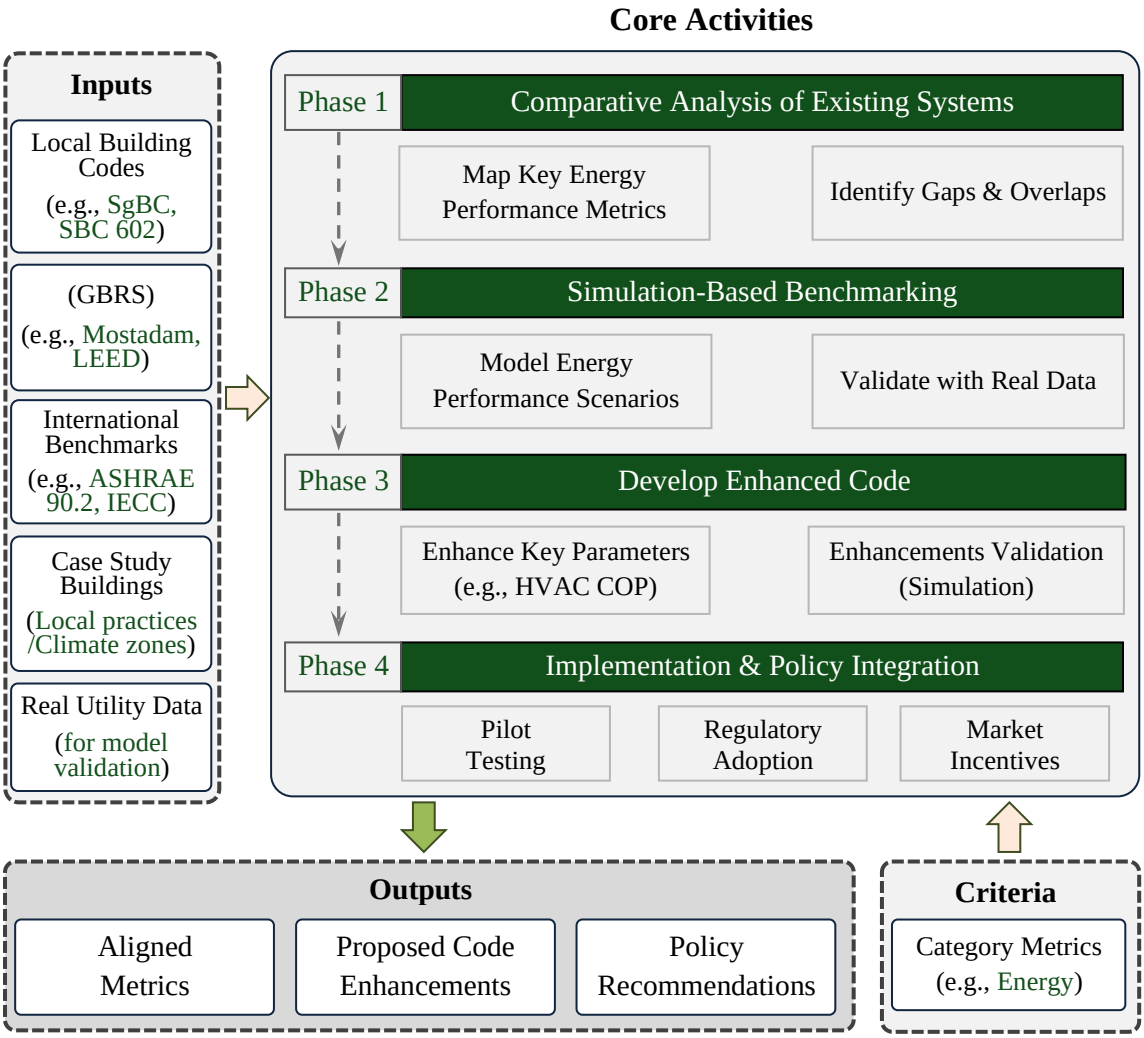

Figure 31: Proposed framework flowchart

5.1. Inputs

The foundational elements that guide the analysis and development process in this framework include several key inputs. Local building codes, such as SgBC and SBC 602, provide the regulatory baseline for assessment. GBRS, including Mostadam and LEED, offer structured sustainability criteria that can complement or enhance local codes. International benchmarks, such as ASHRAE 90.2 and IECC, serve as reference standards to align performance expectations with global best practices. Case study buildings, selected to reflect diverse local climate zones and construction practices, enable context-specific evaluation. Finally, real utility data is incorporated to validate simulation models, ensuring that performance assessments and proposed enhancements are grounded in actual building energy use.

5.2. Criteria

The criteria are used to classify and assess performance metrics, with a primary emphasis on key sustainability aspects such as energy efficiency. They provide a structured basis for evaluating and comparing the effectiveness of various building code elements and rating system components.

5.3. Core Activities

The core activities of the framework are organized into four sequential phases, each contributing to a systematic methodology for assessing, enhancing, and integrating improved building codes.

Phase 1: Comparative Analysis of Existing Systems

This phase aligns with chapter 3 of this study and involves mapping key energy performance metrics and identifying gaps and overlaps among the various building codes and rating systems. Table 7 summarizes the energy performance metrics.

Phase 2: Simulation-Based Benchmarking

This phase focuses on developing energy performance models as shown in Table 23 and validating these models using real-world utility data to ensure reliability and contextual accuracy. This phase aligns with chapter 4 of this study and starts with determining the criteria for selecting the case study based on:

- Representative of local construction practices.
- Cover major climate zones (e.g., hot-humid, arid, moderate).

Table 23: Proposed Scenarios

Scenario	Purpose
Existing Cases	Existing building performance (benchmark).
Local Code	Assess compliance with current regulations.
Rating System	Test against certification criteria.
Improvement Approach	Proposed improved code (e.g., adjusted COP).

Phase 3: Develop Enhanced Code

This phase aims to refine critical performance parameters such as HVAC Coefficient of Performance (COP) and to validate proposed enhancements through simulation studies as done in section 4.5.3.

Phase 4: Implementation & Policy Integration

Finally, this phase includes pilot testing of the enhanced code, facilitating its adoption into regulatory frameworks, and proposing market-based incentives to support its implementation. These components, Pilot Testing, Regulatory Adoption, and Market Incentives are detailed below to illustrate how they collectively ensure the successful integration and real-world impact of the enhanced code.

Pilot Testing involves applying the enhanced building code to selected new construction projects and monitoring the actual energy performance against simulation results. This step is critical for validating the code's effectiveness in real-world conditions.

Regulatory Adoption focuses on engaging with relevant authorities, such as the Saudi Building Code National Committee (SBCNC), to formally propose updates to the national code. This process ensures that the enhanced standards align with broader policy directives, particularly the sustainability objectives outlined in Vision 2030.

Market Incentives aims to encourage adoption of the enhanced code by introducing supportive mechanisms such as fast-tracked permitting for projects meeting higher performance tiers and tax incentives for developers who implement the improved standards. Together, these steps form the foundation for effective policy integration and market transformation.

5.4. Outputs

The final outcomes of the framework comprise a set of aligned metrics, proposed code enhancements, and policy recommendations. The aligned metrics offer consistent and

harmonized performance indicators that facilitate comparison and integration across various systems. The proposed code enhancements provide target recommendations for updating building regulations to improve energy performance and sustainability outcomes. Lastly, the policy recommendations deliver strategic guidance to support the effective integration of the enhanced code into existing regulatory structures, promoting broader adoption and long-term impact.

This systematic framework offers a versatile methodology for researchers, policymakers, and industry practitioners, with potential applications extending beyond energy efficiency to encompass water conservation, sustainable materials, and indoor environmental quality. Its adaptable structure allows for implementation across diverse geographical regions and climatic conditions.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

This study investigated the effective integration of GBRSs into local building codes, using SgBC [63] as a case study. It benchmarked key energy-related criteria in the SgBC against SBC 602 [83], Mostadam, and LEED v4.1 for homes, aiming to identify opportunities for improvement. Based on this comparative analysis, the study proposed and tested enhancements to the SgBC, evaluated through detailed simulation scenarios.

To achieve these objectives, the research first conducted a comparative evaluation of energy performance metrics across the four frameworks. A key focus was the divergence in energy performance measurement approaches: SBC 602 adopts a prescriptive method, while SgBC introduces zEPI as a performance-based element alongside with the prescriptive method of SBC 602. LEED v4.1 uses the HERS Index, Mostadam O+E tracks EUI, and Mostadam D+C evaluates improvement over the ASHRAE 90.2 baseline.

A simulation-based analysis was conducted to examine energy performance across these regulatory frameworks and to assess the effectiveness of the SgBC and SBC 602 under varying climatic conditions. The first simulation set evaluated an existing residential building (Case A) across eight Saudi cities, comparing its performance with SBC 602, ASHRAE 90.2, and IECC reference models. This highlighted how climatic differences influence building performance and certification outcomes.

The second simulation set aligned the analysis with typical buildings in Dhahran (Case B), Jeddah (Case C), and Riyadh (Case D). It assessed the performance of diverse local jurisdictions and regulatory environments. Each simulation set included three phases:

- Phase I: Thermal characteristics
- Phase II: Full building envelope including airtightness
- Phase III: Integration of HVAC efficiency, especially COP

The simulation results yielded the following key observations:

1. SBC 602 outperformed ASHRAE 90.2 in envelope performance but lagged behind in overall energy efficiency in six of eight cities.
2. SBC 602 exhibited climate adaptability, with 12–14% improvement in harsh zones versus 2–7% in temperate ones.
3. All scenarios, including SBC 602-compliant models, ASHRAE baseline, and existing buildings, failed to meet LEED's HERS 70 threshold
4. The IECC performed best, achieving 13–22% improvements over ASHRAE baselines, while SBC 602 showed only 6–14%.
5. Extreme climates (e.g., Jizan, Jeddah) had 2–3× higher EUI than temperate zones like Abha, indicating a need for stricter regional standards.

6. Mostadam rankings showed inconsistency with zEPI: scenarios with higher zEPI sometimes received better scores, indicating EUI plays a stronger role in the final rating.

7. Mostadam D+C consistently awarded more points than Mostadam O+E for equivalent cases.

8. Thermal characteristics proved to be the primary drivers of efficiency; airtightness had limited impact, while COP significantly affected both energy use and CO_2 emissions.

9. LEED's performance thresholds remain challenging under Saudi conditions.

The study introduced a refinement phase by adjusting COP values to meet a zEPI threshold of 50. These adjustments led to a consistent 4% improvement over the ASHRAE 90.2 baseline and brought all scenarios within the desired zEPI range. From this, a new threshold ranking was established per climatic zone.

Moreover, previous studies [69], [70] recommended expanding SBC 602's climate classification from three to five zones. This study supports that recommendation by demonstrating significant performance variation across regions. It also identified limitations in Mostadam's uniform benchmarking, which fails to account for climate-specific conditions. As a solution, the study developed a climate-specific benchmarking model, establishing minimum Mostadam performance thresholds per zone to ensure fair and accurate evaluation.

The study further assessed the large-scale impact of SBC 602 improvements on new residential construction. Using GASTAT permit data as a proxy for annual construction rates, and applying a residential electricity tariff, the analysis projected substantial benefits:

- Energy savings of up to 182 million kWh/year
- CO_2 emissions reduction of 126 million kg/year
- Cost savings exceeding 156 million SAR under the current SBC 602, with the adjusted code offering 13% greater efficiency.

While the current SBC 602 achieves savings of up to 11.9%, the adjusted version reaches 24.9%, clearly demonstrating the effectiveness of the proposed modifications.

Finally, the research provided a framework for enhancing building code performance, tailored to Saudi Arabia's diverse climatic conditions. Beyond energy efficiency, the proposed methodology is adaptable for evaluating other sustainability dimensions, such as water conservation, sustainable materials, and indoor environmental quality.

The developed framework offers practical value for policymakers, researchers, and industry practitioners, supporting informed decision-making and promoting alignment with national and international sustainability goals.

6.2 Recommendations

This study supports ongoing efforts to promote sustainable building practices in Saudi Arabia by aligning local codes with global sustainability benchmarks. This alignment can reduce the environmental footprint, enhance energy efficiency, and support Vision 2030 objectives. The proposed framework provides an actionable roadmap for policymakers, architects, and engineers to advance green building practices in the region.

It is recommended that:

1. SBC 602 be enhanced to incorporate dynamic COP requirements tailored to each climatic zone, given the significant impact of COP on energy consumption.

2. The modification of SBC 602 should integrate the following three key elements:

    - Enforce compliance with the prescriptive energy performance standards outlined in SBC 602 to ensure consistent and reliable energy efficiency.

    - Mandate the use of zEPI as a performance verification tool, requiring buildings to achieve a zEPI score below 50 to meet sustainability targets.

    - Integrate EUI tailored to each climatic zone as a secondary performance metric to complement zEPI. Additionally, Mostadam's ranking system should be adapted for each climatic zone, ensuring climate-specific benchmarks that reflect regional variations and provide more accurate performance assessments.

3. Transition SgBC from a voluntary to a mandatory code to fully capitalize on its significant positive impact on energy efficiency and sustainability.

6.3 Recommendations for Future Work

Based on the highlighted findings and limitations of this study, the following recommendations are proposed to address existing challenges and guide future research:

1. Broaden the Scope of Sustainability Criteria: Extend the proposed framework by integrating water efficiency, materials, and indoor environmental quality considerations. This comprehensive approach would enhance the alignment of Mostadam with SgBC, addressing broader sustainability goals.

2. Conduct Longitudinal Studies: Perform long-term assessments to evaluate the real-world performance of buildings constructed under the enhanced codes, focusing on energy efficiency, environmental impact, and sustainability. This approach can overcome the time constraints of the current study and provide insights into the lasting benefits of the proposed framework.

3. Validate the Framework with Stakeholders: Engage industry stakeholders, regulatory bodies, and practitioners to validate the framework, address practical implementation challenges, and ensure smooth adaptation. This can help navigate regulatory complexities and foster stakeholder support.

4. Adapt Framework for Broader Contexts: Investigate the applicability of the framework in regions beyond Saudi Arabia, considering different regulatory structures, socio-economic conditions, and cultural dimensions. This will help overcome the geographic focus limitation and enhance the framework's relevance to diverse climates and markets.

5. Strengthen Data Collection and Analysis: Future studies should prioritize comprehensive data collection from case studies, expert discussions, and fieldwork to provide in-depth analysis. Enhanced data availability will mitigate the data limitations encountered in this study.

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Vitae

Name	: Saly Ahmed Mohammed Abdou
Nationality	: Egyptian
Date of Birth	: 6/24/1995
Email	: engsalyabdou@gmail.com
Address	: Al-Mahalla Al-Kubra, Postal code 31952, Gharbia, Egypt
Research Interests	: ➢ Sustainable architecture ➢ Building performance and green building certifications ➢ Smart cities and digital transformation
Academic Background	: ➢ B.Sc. in Architectural Engineering (Very Good with Honors) 6th Rank, Mansoura University, Egypt. ➢ M.Sc. in Architectural Engineering, King Fahd University of Petroleum and Minerals, Saudi Arabia.
Professional Experience	: ➢ Teaching Assistant at multiple institutions including: ▪ King Fahd University of Petroleum and Minerals ▪ Faculty of Fine Arts, Mansoura University ➢ LEED "Green Associate" Credential ID: 11592328-GREEN-ASSOCIATE ➢ Senior Architect, EMARA Designs_Construction Company.
Publications & Presentations	: "Technology Readiness Level Assessment of Smart Cities: Case of London"– Presented at the International Open Innovation and Digital Transformation Conference, IEEE Bahrain, March 2024 (Under Review).
Further Information	: https://drive.google.com/drive/folders/1CX8VkSi63nRPG4HjM6bpoKoz7jJQSYvB?usp=sharing