Towards Energy-Efficient Residential Buildings In Jeddah, Saudi Arabia

Exploring Energy Retrofitting Options And Assessing Their Feasibility

Ahmed Felimban

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Towards Energy-Efficient Residential Buildings In Jeddah, Saudi Arabia

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Dissertation

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List of abbreviations

AAEC	Average Annual Energy Consumption
ACH	Air Change per Hour
ACH50	Air Changes per Hour at 50 pascals pressure differential
BDT	Blower Door Test
BOE	Barrels of oil equivalent
CDD	Cooling Degree Days
COP	Coefficient of Performance
CSS	Concrete Skeleton Structure
EIFS	External Insulation Finishing System
EPS	Expanded Polystyrene Insulation
ERA	Energy Retrofitting Application
ETI	Electricity Tariff Increasing
GCC	Gulf Cooperation Council
IEA	International Energy Agency
KAPSARC	King Abdullah Petroleum Studies and Research Centre
KPI	Key Performance Indicator
KSA	Kingdom of Saudi Arabia
MOMRA	Ministry of Municipal and Rural Affairs
OS	Oil Selling
R&D	Research and Development
SBC	Saudi Building Code
SDB	Social Development Bank
SDME	Solar Decathlon Middle East
SEEC	Saudi Energy Efficiency Centre
SPT	Simple Payback Time
UAE	United Arab of Emirates
WWR	Window to Wall Ratio
XPS	Extruded Polystyrene Insulation

Abstract

The thesis investigates the energy retrofitting of existing residential buildings in the Kingdom of Saudi Arabia (KSA), the building sector responsible for a significant proportion of the nation's energy consumption. The research introduces a comprehensive methodology tailored for the unique architectural and social contexts of KSA, aimed at significantly improving energy efficiency and thereby aiding the country in achieving its net-zero emissions target for 2060. Utilizing a case study, the methodology incorporates a detailed analysis of energy performance, identifies suitable retrofitting measures, and evaluates their cost-effectiveness.

The study extends beyond the technical aspects of energy retrofitting to address its social relevance. It posits that implementing such measures can lead to substantial energy savings, improved indoor comfort, and superior housing quality. These interventions can also foster greater societal awareness of energy efficiency, counteracting the primary factors contributing to increased electricity costs.

Despite the manifold benefits, the research identifies potential resistance from residents, which could arise from heightened expectations of energy upgrade providers. Interestingly, this reluctance may serve as a catalyst for providers to improve the quality of their products and services, ultimately enhancing market standards for energy-efficient solutions. Furthermore, the thesis argues that energy retrofitting could stimulate job creation and elevate the status of architectural specialties, thereby supporting broader economic development and social well-being.

The thesis concludes by recommending that state decision-makers actively incentivize energy retrofitting to harvest its multitude of benefits, from enhancing energy efficiency to contributing to economic growth and sustainable development. The proposed methodology offers a robust framework for stakeholders, paving the way for a more energy-efficient, economically viable, and socially responsible residential building sector in KSA.

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Summary

In recent years, the study of energy retrofitting applications in buildings has garnered international interest due to its proven capacity for enhancing energy efficiency. Within the context of the Kingdom of Saudi Arabia (KSA), the building sector constitutes a major consumer of the nation's primary energy resources. Specifically, residential buildings are responsible for approximately half of the daily electricity consumption in the building sector. The past decade has witnessed a surge in awareness and understanding of energy efficiency, particularly following the launch of Saudi Vision 2030 in 2018. To further this agenda, the Saudi government has initiated multiple programs aimed at bolstering energy efficiency. For example, as of July 2021, an updated Saudi Building Code (SBC) has been mandated for all new residential construction projects. Despite this, existing buildings have shown only marginal improvements in energy consumption levels. Although the state has launched several initiatives focused on improving the energy performance of household appliances and lighting products, there is a compelling need to address the energy efficiency of the building fabric itself. Notably, there is a dearth of comprehensive research specifically aimed at identifying and implementing energy-efficient and cost-effective solutions for existing residential buildings in KSA.

The primary issue tackled in this dissertation is the absence of suitable solutions and guidelines for improving the energy performance of existing residential buildings in the Kingdom of Saudi Arabia (KSA). The overarching objective of this research is to advocate for energy retrofitting measures that offer not only significant energy savings but also cost-effective benefits for both users and the state. More specifically, the study aims to equip architects and designers with guidance for enhancing the energy efficiency of existing structures. It also seeks to inform policy-makers on how to allocate financial resources effectively for the application of energy retrofitting in residential buildings, while providing fundamental guidelines for design professionals.

This dissertation explores the interplay between design choices aimed at energy savings and cost-effective solutions, while also informing policy-making decisions. At the starting point, we looked to the energy savings possibilities. To do so, we explored the problem existence and the main contributor of high energy consumption (buildings or users). We conducted a survey within a specific context (Jeddah) in KSA. The results showed the different factors of users contribution in the energy performance of residential buildings. At the same time, the results emphasizes that

70% of residential buildings have no thermal insulation which is aligned with the national statistics. The potential of improving the energy performance of existing residential buildings was obvious which require further investigation.

In the subsequent phase of the research, a framework was developed to delineate various parameters, with the aim of generating contextually relevant solutions. The thesis initiated this framework by sketching out the cultural backdrop, incorporating both social and financial aspects. This was followed by an overview of existing literature, emphasizing recent studies, and then identifying challenges related to energy retrofitting design, including climatic considerations and energy performance metrics. The research proceeded to assess the current state of the building stock and the construction methods employed. Specific design parameters and Key Performance Indicators (KPIs) were then spotlighted for future use. Concluding this segment, the thesis presented an array of generic energy retrofitting enhancement options. Consequently, the framework established particular parameters to guide the next steps of the investigation.

In the ensuing phase, the thesis evaluates and validates potential energy savings through the use of a digital simulation tool, DesignBuilder, across various energy retrofitting scenarios. Existing literature reveals that the investigation of different savings measures yields a range of energy savings, contingent on the specific measures implemented. In this dissertation, simulation outcomes corroborate the energy-saving potential of fundamental upgrade measures, such as window replacement and the addition of insulation to walls and roofs. However, a critical consideration for generating accurate energy savings results lies in the need to investigate infiltration rates, as these have a significant impact on final outcomes and, consequently, on financial considerations.

In the financial analysis stage, the thesis quantifies renovation-related expenses, encompassing current energy costs, initial renovation outlays, and maintenance expenses. Various perspectives were employed to explore potential payback options, such as investment costs (both with and without profit), as well as payback mechanisms like energy savings, oil sales, and/or electricity tariff increases. This phase yielded eight alternative strategies tailored to the Jeddah context, underscoring the financial viability of implementing energy retrofitting measures in residential buildings. A comparative analysis of these alternatives revealed shorter payback periods when government support is available, while options lacking such support exhibited longer payback timelines. Therefore, governmental backing of energy retrofitting initiatives is likely to produce positive outcomes for the state, benefits that would subsequently permeate the market and community, as subsequent phases of the thesis will elaborate these consequences.

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In the discussion of consequences, this dissertation scrutinizes both the immediate and long-term ramifications of implementing energy retrofitting measures in the city of Jeddah. Utilizing three distinct case models, the research evaluates their effects on a range of key indicators, such as energy savings, CO2 emissions, oil sales, capital costs, and payback periods. The analysis highlights the essential role of governmental support in surmounting the various challenges associated with energy retrofitting. By doing so, the state can achieve meaningful gains, both environmentally and financially.

In summary, the research culminates in four principal recommendations for advancing energy efficiency in the Kingdom of Saudi Arabia:

1. Create a specialized sub-committee or association within the SEEC that focuses specifically on energy retrofitting applications for existing buildings, and fosters collaboration with international research institutions.

2. Implement and enforce energy efficiency standards tailored for existing structures, bolstered by financial incentives and support programs.

3. Broaden public awareness and education on energy efficiency through extensive dissemination efforts.

4. Invest in research and development to advance innovative technologies and materials that promote sustainable construction.

Additionally, the practice of energy efficiency requires further education and collaboration among all stakeholders involved, including policymakers, architects, designers, market providers, and end-users. This unified approach is crucial for achieving comprehensive energy efficiency gains.

Samenvatting

De afgelopen jaren heeft het onderzoek naar toepassingen voor energieretrofiting in gebouwen internationale belangstelling gekregen vanwege het bewezen vermogen ervan om de energie-efficiëntie te verbeteren. Binnen de context van het Koninkrijk Saoedi-Arabië (KSA) vormt de bouwsector een belangrijke verbruiker van de primaire energiebronnen van het land. Concreet zijn woongebouwen verantwoordelijk voor ongeveer de helft van het dagelijkse elektriciteitsverbruik in de bouwsector. Het afgelopen decennium is het bewustzijn en begrip van energie-efficiëntie toegenomen, vooral na de lancering van Saudi Vision 2030 in 2018. Om deze agenda te bevorderen heeft de Saoedische regering meerdere programma's geïnitieerd die gericht zijn op het versterken van de energie-efficiëntie. Sinds juli 2021 is er bijvoorbeeld een bijgewerkte Saoedische bouwcode (SBC) verplicht gesteld voor alle nieuwe woningbouwprojecten. Desondanks hebben bestaande gebouwen slechts marginale verbeteringen in het energieverbruik laten zien. Hoewel de staat verschillende initiatieven heeft gelanceerd die gericht zijn op het verbeteren van de energieprestaties van huishoudelijke apparaten en verlichtingsproducten, bestaat er een dwingende noodzaak om de energie-efficiëntie van het bouwweefsel zelf aan te pakken. Er is met name een gebrek aan alomvattend onderzoek dat specifiek gericht is op het identificeren en implementeren van energie-efficiënte en kosteneffectieve oplossingen voor bestaande woongebouwen in KSA.

Het belangrijkste probleem dat in dit proefschrift wordt aangepakt, is het ontbreken van geschikte oplossingen en richtlijnen voor het verbeteren van de energieprestaties van bestaande woongebouwen in het Koninkrijk Saoedi-Arabië (KSA). De overkoepelende doelstelling van dit onderzoek is het pleiten voor energie-retrofitmaatregelen die niet alleen aanzienlijke energiebesparingen opleveren, maar ook kosteneffectieve voordelen bieden voor zowel gebruikers als de staat. Meer specifiek heeft de studie tot doel architecten en ontwerpers te voorzien van richtlijnen voor het verbeteren van de energie-efficiëntie van bestaande constructies. Het is ook bedoeld om beleidsmakers te informeren over hoe ze financiële middelen effectief kunnen toewijzen voor de toepassing van energierenovatie in woongebouwen, terwijl het tegelijkertijd fundamentele richtlijnen biedt voor ontwerpprofessionals.

Dit proefschrift onderzoekt de wisselwerking tussen ontwerpkeuzes gericht op energiebesparing en kosteneffectieve oplossingen, terwijl ook beleidsbeslissingen worden onderbouwd. Bij het uitgangspunt hebben we gekeken naar de energiebesparingsmogelijkheden. Om dit te doen, hebben we het bestaan van het probleem en de belangrijkste oorzaak van het hoge energieverbruik (gebouwen of gebruikers) onderzocht. We hebben een onderzoek uitgevoerd binnen een specifieke context (Jeddah) in KSA. De resultaten lieten de verschillende factoren zien van de bijdrage van gebruikers aan de energieprestaties van woongebouwen. Tegelijkertijd benadrukken de resultaten dat 70% van de woongebouwen geen thermische isolatie heeft, wat overeenkomt met de nationale statistieken. Het potentieel om de energieprestaties van bestaande woongebouwen te verbeteren was duidelijk en vergt verder onderzoek.

In de daaropvolgende fase van het onderzoek werd een raamwerk ontwikkeld om verschillende parameters af te bakenen, met als doel contextueel relevante oplossingen te genereren. Het proefschrift vormde de aanzet tot dit raamwerk door de culturele achtergrond te schetsen, waarbij zowel sociale als financiële aspecten werden meegenomen. Dit werd gevolgd door een overzicht van de bestaande literatuur, waarbij de nadruk werd gelegd op recente onderzoeken, en vervolgens de uitdagingen werden geïdentificeerd die verband houden met het ontwerp van energierenovatie, inclusief klimaatoverwegingen en energieprestatiestatistieken. Het onderzoek ging verder met het beoordelen van de huidige staat van het gebouwenbestand en de toegepaste bouwmethoden. Specifieke ontwerpparameters en Key Performance Indicators (KPI's) werden vervolgens onder de aandacht gebracht voor toekomstig gebruik. Ter afsluiting van dit segment presenteerde het proefschrift een reeks generieke opties voor verbetering van de energie-retrofit. Het raamwerk heeft specifieke parameters vastgelegd om de volgende stappen van het onderzoek te begeleiden.

In de daaropvolgende fase evalueert en valideert het proefschrift potentiële energiebesparingen door het gebruik van een digitale simulatietool, DesignBuilder, in verschillende energieretrofitscenario's. Uit bestaande literatuur blijkt dat het onderzoek naar verschillende besparingsmaatregelen een scala aan energiebesparingen oplevert, afhankelijk van de specifieke maatregelen die worden genomen. In dit proefschrift bevestigen simulatieresultaten het energiebesparingspotentieel van fundamentele upgrademaatregelen, zoals het vervangen van ramen en het toevoegen van isolatie aan muren en daken. Een cruciale overweging voor het genereren van nauwkeurige energiebesparingsresultaten ligt echter in de noodzaak om de infiltratiepercentages te onderzoeken, aangezien deze een aanzienlijke impact hebben op de uiteindelijke resultaten en bijgevolg op financiële overwegingen.

In de financiële analysefase kwantificeert het proefschrift renovatiegerelateerde kosten, waaronder de huidige energiekosten, initiële renovatiekosten en onderhoudskosten. Er werden verschillende perspectieven gehanteerd om potentiële terugverdienopties te verkennen, zoals investeringskosten (zowel met als zonder winst), evenals terugverdienmechanismen zoals energiebesparingen, olieverkoop en/of verhoging van elektriciteitstarieven. Deze fase leverde acht alternatieve strategieën op die waren toegesneden op de context van Jeddah en onderstreepten de financiële haalbaarheid van het implementeren van energieretrofitmaatregelen in woongebouwen. Een vergelijkende analyse van deze alternatieven bracht kortere terugverdientijden aan het licht wanneer overheidssteun beschikbaar is, terwijl opties waarbij dergelijke steun ontbrak, langere terugverdientijden vertoonden. Daarom zal overheidssteun voor energierenovatie-initiatieven waarschijnlijk positieve resultaten voor de staat opleveren, voordelen die vervolgens de markt en de gemeenschap zouden doordringen, aangezien de volgende fasen van het proefschrift deze consequenties zullen uitwerken.

In de discussie over de gevolgen onderzoekt dit proefschrift zowel de directe als de lange termijn gevolgen van het implementeren van energierenovatiemaatregelen in de stad Jeddah. Aan de hand van drie afzonderlijke casemodellen evalueert het onderzoek de effecten ervan op een reeks sleutelindicatoren, zoals energiebesparingen, CO2-uitstoot, olieverkoop, kapitaalkosten en terugverdientijden. De analyse benadrukt de essentiële rol van overheidssteun bij het overwinnen van de verschillende uitdagingen die gepaard gaan met energierenovatie. Door dit te doen kan de staat betekenisvolle winsten behalen, zowel op ecologisch als financieel vlak.

Samenvattend culmineert het onderzoek in vier belangrijke aanbevelingen voor het bevorderen van de energie-efficiëntie in het Koninkrijk Saoedi-Arabië:

1. Creëer een gespecialiseerde subcommissie of vereniging binnen de SEEC die zich specifiek richt op energie-retrofit-toepassingen voor bestaande gebouwen, en samenwerking bevordert met internationale onderzoeksinstellingen.

2. Implementeer en handhaaf energie-efficiëntienormen die zijn afgestemd op bestaande structuren, ondersteund door financiële prikkels en ondersteuningsprogramma's.

3. Verruim het publieke bewustzijn en de voorlichting over energie-efficiëntie door middel van uitgebreide verspreidingsinspanningen.

4. Investeer in onderzoek en ontwikkeling om innovatieve technologieën en materialen te bevorderen die duurzame constructie bevorderen.

Bovendien vereist de praktijk van energie-efficiëntie verdere educatie en samenwerking tussen alle betrokken belanghebbenden, inclusief beleidsmakers, architecten, ontwerpers, marktaanbieders en eindgebruikers. Deze uniforme aanpak is van cruciaal belang voor het behalen van alomvattende winst op het gebied van energie-efficiëntie.

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1 Introduction

1.1 Background

The building sector in the Kingdom of Saudi Arabia (KSA) consumes a significant portion of the country's primary energy, with residential buildings accounting for approximately half of the daily electricity consumed by buildings [1]. The Saudi Energy Efficiency Center (SEEC) has reported that the building sector represents a substantial contributor to primary energy consumption in the region, consuming an estimated 29% of total energy, or roughly 1.3 million barrels of oil equivalent (BOE) [2].

Furthermore, research conducted by the King Abdullah Petroleum Studies and Research Center (KAPSARC) has revealed that residential buildings alone account for just below 50% of the total daily electricity consumption by buildings in the KSA, representing slightly above 0.6 million BOE [3]. The rapid growth of housing construction, coupled with an annual increase of 5-8% in electricity demand, is also a cause for concern, as it could lead to a potential oil crisis by 2035 if the oil consumption rate equals the production rate [4]. These findings underscore the significant impact of the building sector on regional energy consumption patterns and highlight the need for more effective strategies to promote energy efficiency in the construction and maintenance of buildings.

The Saudi Energy Efficiency Center (SEEC) has implemented and participated in several measures to improve energy consumption nationally [5]. These measures include upgrading the building code in partnership with the Saudi Building Code (SBC) committee, which has included energy requirement guidelines [6]. Furthermore, the SEEC has launched initiatives such as Air Conditioning (AC) replacement, lighting replacements, and improving household appliances to reduce energy consumption [7]. Additionally, the SEEC requires examination, control, and certification of new buildings to ensure compliance with energy efficiency regulations and standards. Such actions are essential to promote energy-efficient buildings and reduce energy consumption in the KSA.

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In the KSA, the primary obstacle in the current scenario is the exorbitant monthly electricity bills encountered by building occupants due to the recent threefold escalation of electricity tariffs [8]. This hike in energy tariffs has a pronounced effect during summer months, characterized by surging prices [9]. The electricity provider has implemented a fixed-rate plan to mitigate consumer impact [10]. Furthermore, monthly electricity bills have been further inflated by the upsurge of VAT from 5% to 15%. Despite implementing these measures, users lack awareness and knowledge of energy efficiency as they are uncertain why their monthly electricity bills are higher than before 2018, particularly during the summer [11].

In hot-arid regions, multiple studies have demonstrated the potential of energy upgrade measures for residential buildings using various methods [12]–[19]. However, in the KSA, recent efforts to enhance energy efficiency have primarily focused on newly constructed buildings, with insufficient attention given to existing buildings. The emphasis has been placed on upgrading household appliances and electrical devices [7]. While implementing energy retrofitting measures is crucial, comprehending the holistic Energy Retrofitting Application (ERA) model is even more critical to establish suitable solutions for each case. Thus, a comprehensive understanding of the beneficiaries' needs (users, market, state) and the benefits of such applications is essential for the successful implementation of the ERA [16], [20], [21].

In light of the significant contribution of residential buildings to the daily electricity consumption in Saudi Arabia, there is a pressing need to implement energy-efficient measures to lower the overall energy demand. Implementing the ERA is critical in improving the energy performance of existing buildings and reducing the monthly electricity bills of users while ensuring adequate thermal comfort [22]. Furthermore, the ERA has enormous potential for both economic and social relevance, as it can lead to sustainable long-term benefits for the state's economy and the well-being of its inhabitants. Therefore, there is an urgent need to prioritize the implementation of the ERA to promote energy efficiency and reduce energy consumption in the residential sector.

1.2 Scientific problem

The potential of the ERA to upgrade the energy performance of existing residential buildings has been investigated in different studies. Studies in respect of energy upgrading measures have demonstrated potential savings ranging from 37% up to 80% when applying different energy upgrading measures (wall insulation, roof insulation , windows (WWR, glazing and shading) and AC), which shows a high probability of successful application [23]–[32].

Although the potential of energy upgrades has been investigated and identified, the resulting outcomes are presented in overall recommendations without including the recent changes in living expenses and energy prices [29], [30], [32]. As stated earlier, the state regulations and initiatives provide specific energy requirements for new buildings but not for existing ones, and further investigation into how the ERA could be economically and socially feasible is needed [6]. Therefore, the ERA for building envelope needs detailed guidelines for a model method to suit individual case conditions.

The energy upgrading of existing residential buildings is complex, incorporating different parameters such as architectural energy design, user behaviors and comfort needs, energy efficiency regulations, and economic aspects, including available investments and possible business models [21], [28], [34], [35]. Designing ERA models requires addressing all of the different specifications of these parameters that define the necessary decision approaches from the state. In addition, the ERA's energy upgrade design model involves different parties, such as users, state representatives, and market representatives, which requires investigating the overall situation and what could benefit all parties. At the same time, the key factor of energy upgrade application for building envelope is not only energy performance but also financial competence, and application consequences are essential for attempting a holistic approach for individual cases [4], [36]–[38].

In the thesis, the authors investigate the impact of user behaviors and the thermal resistance of the building envelope on the energy performance and consumption levels of existing buildings. The objective is to uncover the most practical solutions for improving energy performance in a financially viable way. Therefore, the aim of the thesis is to answer the following question:

What are the most energy-efficient and cost-effective retrofit schemes for upgrading the building envelopes of existing residential buildings in Jeddah, Saudi Arabia, and how can the findings guide architects and decision-makers in implementing energy-saving measures for residential buildings?

This study aims to identify and validate the energy retrofitting schemes that are most appropriate in terms of their cost-effectiveness and energy-saving potential for the building envelopes of existing residential buildings. The results will guide architects and decision-makers on energy-saving measures for residential buildings in Saudi Arabia, with Jeddah serving as a representative case study

Five sub-questions are investigated in order to answer the main research question:

1. **What are the primary factors responsible for the high energy consumption in residential buildings in Jeddah, Saudi Arabia, and what are the key variables influencing the existing energy demand?**

2. **What are the parameters for selecting the most applicable energy retrofitting strategies that can be employed to enhance the energy efficiency of residential buildings in Jeddah, Saudi Arabia?**

3. **To what extent can implementing energy retrofitting scenarios on building envelopes reduce the energy consumption of a mid-rise residential building in Jeddah, Saudi Arabia?**

4. **Which energy retrofitting strategy offers the most cost-effective solutions for implementing energy retrofitting applications (ERAs) into existing residential buildings?**

5. **What is the impact of ERAs on residential buildings in the KSA in terms of their environmental, economic, and social implications?**

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1.3 Methodology

Answering the research question requires different steps, which are demonstrated in this thesis; the potential of ERAs in respect of existing residential buildings in the KSA is also demonstrated. The methodology is used to develop an approach for understanding the local context to provide the most applicable energy upgrading measures within an economic frame. The methods used are as follows:

1. Understanding the local context to highlight the main concerns using the local context survey method.
2. Constructing a framework to set up different parameters for a Jeddah context and demonstrate possible energy upgrade measures.
3. Validating energy-saving possibilities through digital simulation tools.
4. Undertaking a cost–benefit analysis.
5. Highlighting the impact of the Energy Retrofitting Application on residential buildings to accelerate the decisions on implementing ERAs in the near future.

The devised approach will establish methodological procedures for configuring distinct ERA scenarios. This framework is intended to assist decision-makers in implementing ERA measures for existing residential buildings in Jeddah.

The first step of this study is to identify the present challenges that trigger and contribute to the elevated energy consumption of existing residential buildings, specifically mid-rise buildings in Jeddah. A survey is utilized in this thesis to validate the existence of the issue of high energy consumption. Furthermore, distinct variables are presented as indicators of energy performance deficiencies in existing buildings. Notably, the increase in electricity tariffs, user thermal comfort level, and building thermal resistance are prominent factors that demonstrate a correlation. These variables are the primary contributors to the current situation and should not be disregarded when designing energy upgrade solutions. The survey results emphasize the importance of comprehending the local context and the necessity for energy upgrades.

After understanding the need for energy upgrading in the Jeddah context, the second step is to define and illustrate specific parameters to set a solid ground for designing possible energy upgrading measures. The results demonstrate various energy upgrade scenarios using indoor and outdoor interventions for different basic walls.

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Consequently, the third step of this investigation involves delineating specific exemplary case studies that can yield plausible energy-saving outcomes. Initially, design parameters are established that align with the target benchmark. Subsequently, a typical case study is presented, encompassing the building's location and orientation, building fabric characteristics, user profile, and building ownership types. Diverse scenarios are subsequently constructed for different apartments, which are then analyzed and assessed. The results and analysis section reveals that two notable variables, apartment position and infiltration rate, can significantly impact the energy-saving results. In addition, several potential energy upgrade scenarios are derived.

The fourth step of this study involves a cost–benefit analysis to reveal distinct alternatives that can cater to the intended beneficiaries, including the state, market, and users. Initially, the necessary expenses are calculated, including energy, scenario, and maintenance costs. Subsequently, the total costs for each scenario are computed. Next, the payback possibilities are evaluated, necessitating the definition of investment sources and payback strategies. The results section showcases eight unique alternatives with diverse possibilities that demand different decisions regarding which option to implement.

The fifth step of this study broadens the focus to examine the impact of energy retrofitting applications on a city-wide scale. The study highlights the primary challenges of implementing ERAs in Jeddah, with a particular emphasis on environmental, social, economic, and governance concerns. Simultaneously, the study outlines the beneficiaries of ERAs in Jeddah, necessitating justification of the possible decision-making approach. Subsequently, the overall impact of factors such as energy savings, CO2 emissions, payback periods, and oil sales is evaluated. Various models are examined that depend on the type of investment, ultimately leading to different outcomes. The short-term and long-term implications on the state, market, and community levels are then discussed, with the short-term ramifications relating to the necessary actions while the long-term consequences pertain to future impacts.

1.4 Scope of the research

The thesis explores and defines the potential applications for retrofitting mid-rise residential buildings to provide decision-makers with viable models. However, the study requires establishing certain boundary conditions to elucidate the model in greater detail.

The current study investigates energy retrofitting applications at the KSA level. The KSA comprises thirteen regions with five different climate zones with some similarities, and this allows for comparing all regions [1], [29]. Even though these regions are found in one country, variations in factors such as climate, topography, and user behaviors result in distinct cooling and heating needs [39]. Although identifying key parameters is crucial, accounting for these essential parameters would increase the complexity of potential proposals, posing significant challenges for decision-makers. Therefore, in this thesis, the climate parameter was excluded by focusing solely on the Jeddah city climate. However, the proposed methodology is not restricted to this specific region and applies to other geographic areas with differing climates. While the numerical output of the proposed model calculations may vary, the overall approach would remain valid.

The building type for this study was selected based on the recent market growth of mid-rise multifamily buildings [40]. A case study building was also selected as part of the methodology to ensure reliable and focused results. The research methodology's applicability can be extended to other climate regions in the KSA. The study selection of the building case study was intended to represent recent and older mid-rise residential buildings constructed similarly, as explained in Chapter 3. While the case study serves the purpose of identifying a potential energy retrofitting model, the results of the proposed methodology are transferable to other building types.

Since the research aims to investigate energy retrofitting applications in the KSA context, energy performance and total costs must be quantified. On the one hand, the thesis focuses on electricity consumption, which is one indicator used to assess the proposed models. On the other hand, the study investigates the effectiveness of the total cost, including the case's initial costs, the investment sources, and the payback periods and options. The users' comfort regarding adequate ventilation rates and comfort temperatures is a precondition in the calculation.

Given that this research aims to examine energy retrofitting applications in the KSA context, it is necessary to quantify energy performance and total costs. Concerning the former, the thesis is focused on electricity consumption as a key indicator for evaluating the proposed models. In addition, the study evaluates the effectiveness of total costs, which encompass initial case costs, investment sources, payback periods, and options. Furthermore, user thermal comfort levels (as represented by temperature ranges) is a crucial factor in the calculation and design process, particularly in terms of its impact on energy efficiency levels.

In the KSA context, electricity consumption is the primary energy efficiency indicator, explicitly concerning cooling demand [41]. This demand primarily relies on air-conditioning units to lower indoor temperatures. Other devices such as central AC systems and evaporative AC were excluded from the study to prevent interference with the targeted indicator.

1.5 Relevance

1.5.1 Scientific Relevance

The thesis contributes to the knowledge of the cost-effectiveness of applying energy retrofitting measures to increase the energy efficiency of existing building stock [42]. It is distinguished from previous research in that it considers various measures, such as wall insulation upgrades, roof insulation upgrades, window upgrades, and AC unit upgrades, for improving energy efficiency related to cooling demand [29], [30], [32]. Given the complexity of the task, understanding the overall impacts of energy retrofitting is crucial to secure support from key decision-makers. The proposed methodology has generated significant results demonstrating the positive impact of applying energy retrofitting strategies. These findings could encourage state decision-makers to support the application of energy retrofitting measures in existing residential buildings, which would impact the building industry, designers, and the community by improving energy efficiency. The research targets explicitly building designers and state decision-makers. The approach proposed in this study outlines specific steps and requirements for implementing energy upgrades and highlights short- and long-term consequences. The thesis results provide a starting point for energy retrofitting on residential buildings by illustrating the overall effect at the state level and demonstrating its cost-effectiveness. .

1.5.2 Societal Relevance

The energy retrofitting of residential buildings is a socially relevant issue with the potential for significant impacts on society in the KSA. According to recent studies, many residential buildings in the KSA lack thermal insulation, the installation of which can result in significant energy savings, improved indoor thermal comfort, enhanced housing quality, and reduced energy bills for residents [29], [30], [32], [41]. Applying energy retrofitting measures can also increase the awareness of energy efficiency within KSA society by highlighting the primary causes of increased electricity bills and promoting more sustainable energy consumption practices.

Despite the potential benefits, residents may resist low-energy performance measures, which could lead to higher expectations from energy upgrade providers. However, this may also incentivize providers to improve the quality of energy products in the market, enhancing the overall market quality of energy efficiency upgrades. Additionally, energy retrofitting can contribute to job creation and increase the credibility of the architectural specialty, further promoting economic development and social relevance.

Furthermore, energy retrofitting can positively impact various societal sectors, as well as the environment and social resilience. For instance, energy retrofitting can contribute to sustainable development and resilience by reducing the country's dependence on fossil fuels and mitigating the impacts of climate change and natural disasters.

In conclusion, applying energy retrofitting measures has significant social relevance in the KSA by improving energy efficiency, promoting economic development, and contributing to sustainable and resilient built environments. Therefore, promoting and incentivizing energy retrofitting projects is necessary to realize these benefits and achieve sustainable development goals.

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1.6 Research Outline

The sub-questions of the thesis can be used to answer the main research question through a step-by-step approach that divides the research into separate chapters. Chapter 1 introduces the primary problem in the KSA and its relation to residential buildings. In Chapter 2, the problem's existence is assessed and the primary causes of high electricity consumption are identified, with a focus on the city of Jeddah as a case study.

Chapter 3 establishes the necessary framework for proposing specific energy upgrade approaches. This chapter identifies various parameters, including building stock, cultural background, living costs, construction methods, materials, climate, design parameters, and KPIs, which define the scope and are used to outline possible energy upgrade scenarios. The chapter also explores existing issues within the KSA context and illustrates generic possible upgrade scenarios based on different available wall specifications.

Chapter 4 introduces and validates the most applicable upgrading scenarios within a specific case study. The chapter defines the design parameters, benchmarks, and case study description required to simulate the scenarios in a digital program (DesignBuilder). The simulations consider different air change rates per hour (ACH) to illustrate the impact of ACH on the results. The results are used to discuss the annual average energy consumption (AAEC) for the proposed scenarios and the uncertainties involved in the simulation process.

Chapter 5 analyzes the cost–benefit possibilities and presents the cost-effectiveness of different scenarios. This chapter includes calculations of the required cost of the proposed scenarios, their payback possibilities, and available investment sources and payback opportunities. The results are used to discuss the costs and payback options, and determine the ERA's potential in respect of residential buildings in the Jeddah context.

Chapter 6 highlights the specific challenges in respect of ERAs, presenting the primary beneficiaries and the applicable decision-making approach. The chapter also presents a selection of typical residential units for calculating the outcomes at the city-level. Different study models are defined to highlight the possible consequences of ERAs on three levels (state, market, and community) in the short- and long-term.

Finally, Chapter 7 presents the results and draws conclusions in relation to the thesis's central question. In addition, this chapter provides general ERA recommendations. Figure 1.1 illustrates the research steps.

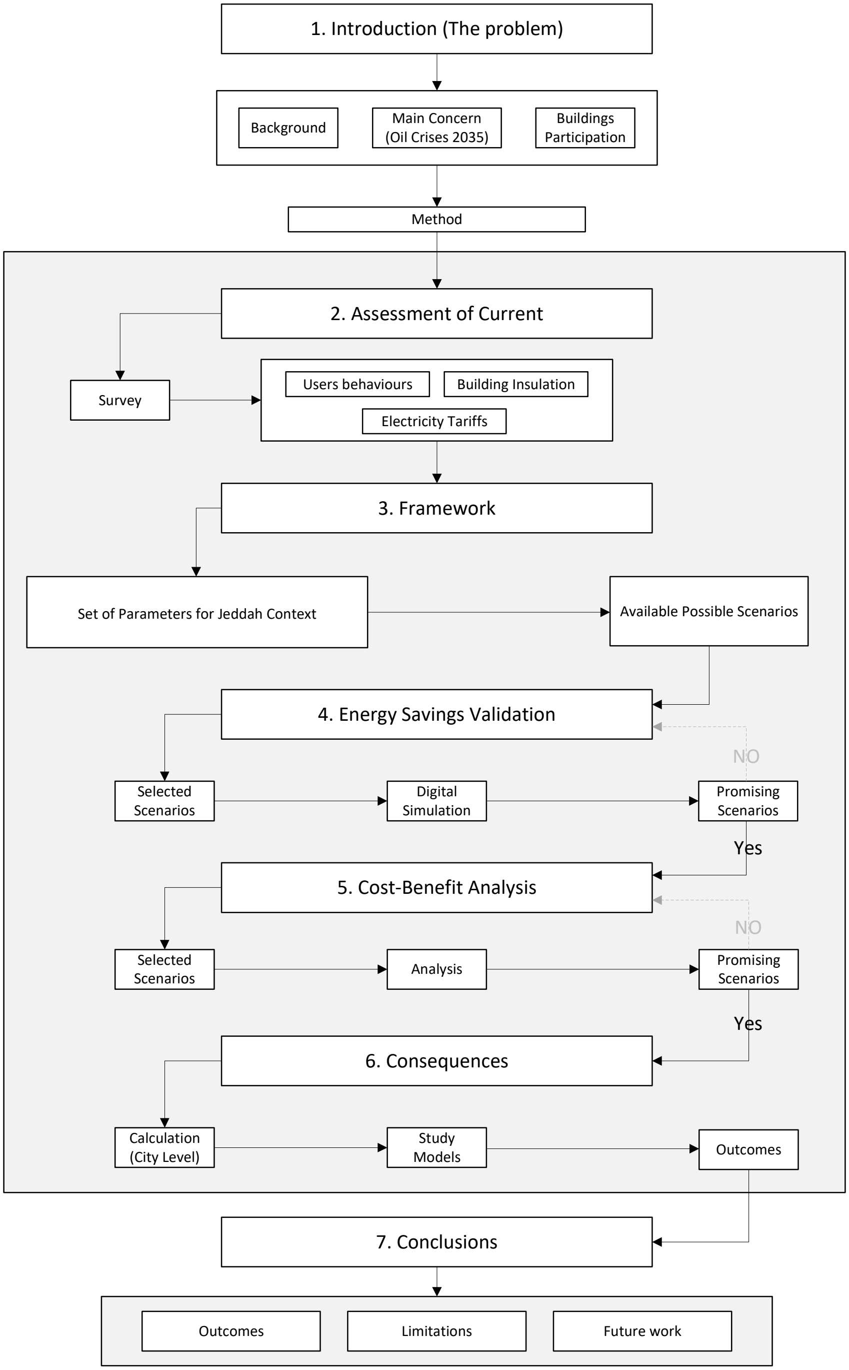

FIG. 1.1 Research outline scheme.

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2 Assessment of Current Energy Consumption in Residential Buildings in Jeddah, Saudi Arabia

The introduction chapter has illustrated the central issues of energy consumption in KSA. However, energy efficiency has been introduced lately in KSA, which requires verifying and understanding the current energy consumption of residential buildings in Jeddah, KSA. Therefore, this chapter clarifies the energy performance of the residential buildings within the Jeddah city context concerning building (thermal insulation, AC units, daylight, window ratio, noise and room size) and user (behaviours, thermal comfort, cultural background, income status, electricity bills and satisfactions). After surveying existing buildings using users' inputs, this chapter claims the energy upgrading necessities of current residential buildings in Jeddah. Besides, chapter 2 was published in a peer-reviewed journal (Buildings) and titled "Assessment of Current Energy Consumption in Residential Buildings in Jeddah, Saudi Arabia" [41].

Section 2.1 introduces energy consumption in KSA, followed by section 2.2, which shows the background and related work. Then section 2.3 identifies the research approach, followed by section 2.4, which shows the results. After that, section 2.5 discusses the outcomes. Finally, section 2.6 clarifies the chapter's conclusion of the need for energy retrofitting investigation.

2.1 Introduction

Many countries invest in renewable energy sources to preserve natural resources for a sustainable future. In the Kingdom of Saudi Arabia (KSA), electricity consumption uses over one-third of the total daily oil production of the country, as shown in Figures 2.1 and 2.2 [4], [43]. Hence, the KSA government has become concerned about its future economy and is investing in sustainability measures.

In April 2016 [44], the KSA government implemented and deployed the Saudi 2030 Vision. In the context of this paper, sustainable development is defined as development that attains the current generation's necessities without inhibiting the needs of future generations [45], [46]. The Saudi 2030 Vision regarding buildings concentrates on developing KSA cities and achieving environmental sustainability [44].

In November 2010, the KSA government introduced the Saudi Energy Efficiency Center (SEEC), and in March 2018, it started functioning after the Saudi 2030 Vision announcement [48]. In 2018, the KSA government announced a $200 billion investment with Soft Bank to produce 200 gigawatts of energy using Concentrated Photovoltaics (PV) solar plants by 2030, which should cover the future projected energy consumption by 2035 [49]. In KSA, currently, buildings consume around 80% of the total electricity generated [7], [19]. Now, the government is investing in renewable energy plants.

Nevertheless, buildings' energy consumption is high. The government has focused on lowering current energy consumption. Buildings' energy consumption is the first concern due to its effect on the total energy consumption. Therefore, the SBC committee implemented a new building code in 2018. Existing buildings cause the current energy consumption, and this problem will remain undeveloped.

A total of 2.32 million new residential units need to be built by 2020, of which 33% were delivered by January 2019 (buildings using the previous building code) [19], [40], [50]. Currently, residential buildings consume around half of the total energy consumption of the building stock due to many defects in the building code, design processes, urban design, and construction applications.

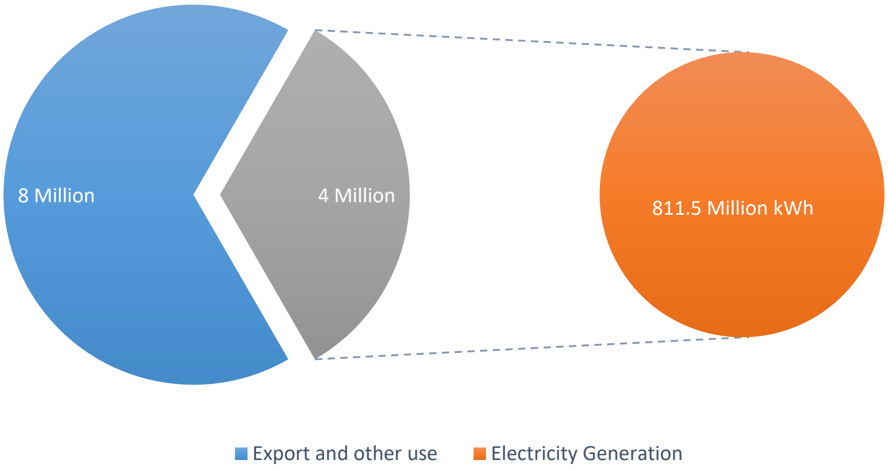

FIG. 2.1 Saudi Oil Daily Production in Barrel and Electricity capacity from daily oil production [4], [43].

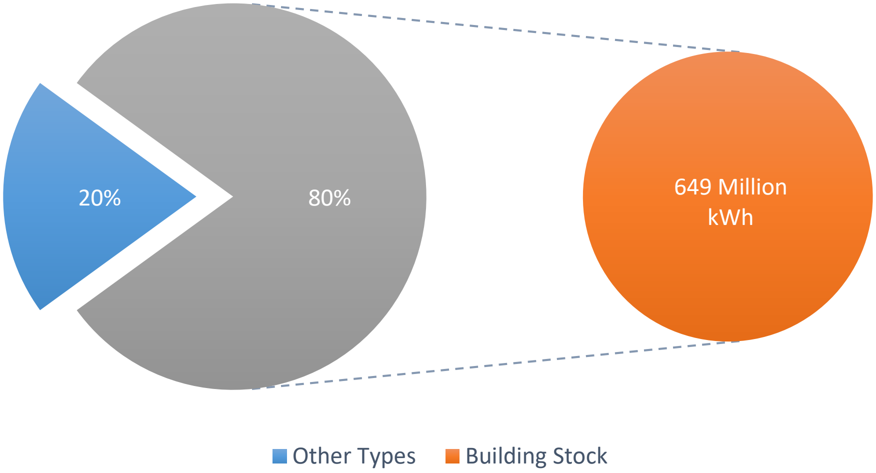

FIG. 2.2 Daily electricity consumption percentage of the building sector compared to other types [47].

Research has illustrated the significant challenges that KSA buildings are facing, such as high electricity consumption, mainly due to air conditioning (AC) units, which are responsible for up to 70% of the electricity consumption of residential buildings, and a lack of insulation in the building envelope (70% of residential buildings are not thermally insulated) [19]. A governmental report showed that refrigerators use twice as much electricity as ACs in the average week [51]. However, the report did not show any energy measurement values that could be compared, such as kWh (Kilowatts times hour). Existing studies do not include the actual energy consumption from all energy users nor show the building envelope's role in how much energy the building uses. Unfortunately, the recent changes and developments in the country are also not included in any of these studies. Thus, there is a need to identify the leading causes of the high energy consumption of buildings. This study has generated a survey with specific criteria that can show the current buildings' energy consumption and the behaviour of its users. No previous studies have considered user behaviour and its effects on energy consumption.

The key driver for energy consumption is the hot–arid climate, which requires the cooling of buildings to provide the desired indoor comfort. The need to lower the consumption of fossil fuels requires immediate improvement in buildings' energy performance for efficient energy use to avoid future economic consequences in the country.

This article aims to evaluate the effect of the behaviour of the current users on the buildings' energy performance and considers the cost aspects. It was not easy to produce more detailed questions in the survey regarding energy consumption. This electronic questionnaire only recorded complete questionnaires; partly completed questionnaires were disregarded. It was also impossible to distinguish, in-depth, how the electricity per household was consumed, such as in cooling, heating, cooking, cleaning, and ironing. The main reason is to gain a broader understanding and identify the leading causes of high energy consumption in buildings. The study used a survey with specific criteria to assess current buildings' energy consumption and the relationship with the behaviour of its users.

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2.2 Background and Related Work

2.2.1 Overview of Current Energy Demand Scenario in the Kingdom of Saudi Arabia

In hot–arid climates, KSA was ranked among the ten countries with the highest energy consumption per capita in 2014 [52]. KSA was also ranked as one of the ten most CO_2-emitting countries in the world [53], [55]. According to the Saudi Energy Efficiency Report [5] published in 2013, the primary energy consumption per capita is over three times higher than the world average. According to a study by Alshibani and Alshamrani [4], electricity generation consumes nearly one-third of the daily KSA oil production. Nevertheless, electricity usage is growing annually by approximately 5–8%, which, based on these facts, would potentially lead to equal oil production and consumption by 2035 [4].

Until now, the building stock has consumed around 80% of the total electricity that the Saudi Electricity Company generates daily. Several authors, including from the King Abdullah Petroleum Studies and Research Center (KAPSARC) [53] in 2018, have stated that the energy consumption of residential buildings accounts for approximately 50% of the total electricity consumption in the building's stock (Figure 2.3) [7], [31], [47], [55]. Remarkably, AC systems account for around 50% of the buildings' stock electricity consumption [7], [19]. KSA contains five different climate regions with high cooling demands, as shown in Figures 2.4 and 2.5, ranging between 40% and 71% for a typical villa's energy consumption [29]. The cooling loads are relatively high in KSA, as seen in Figure 2.5, and urgent intervention is needed to maximise energy efficiency. The city of Jeddah has extremely high cooling demand in KSA, as presented in Figures 2.4 and 2.5.

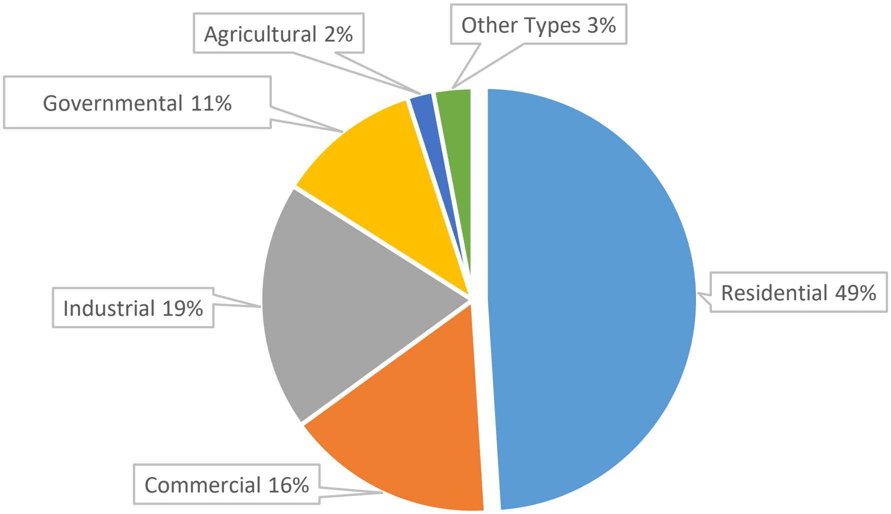

FIG. 2.3 Residential electricity consumption [29].

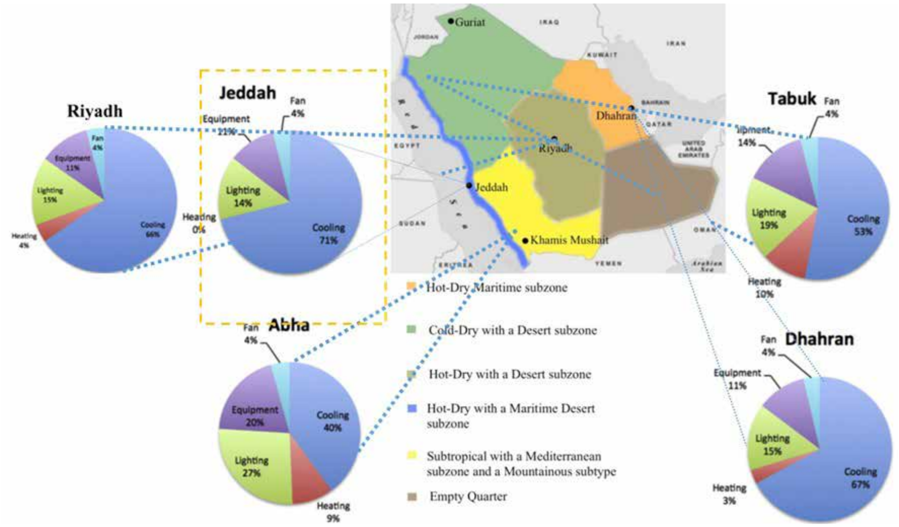

FIG. 2.4 Kingdom of Saudi Arabia (KSA) climate zones and relative energy demands of a typical villa that is 525 m² in size and has two floors [1], [29].

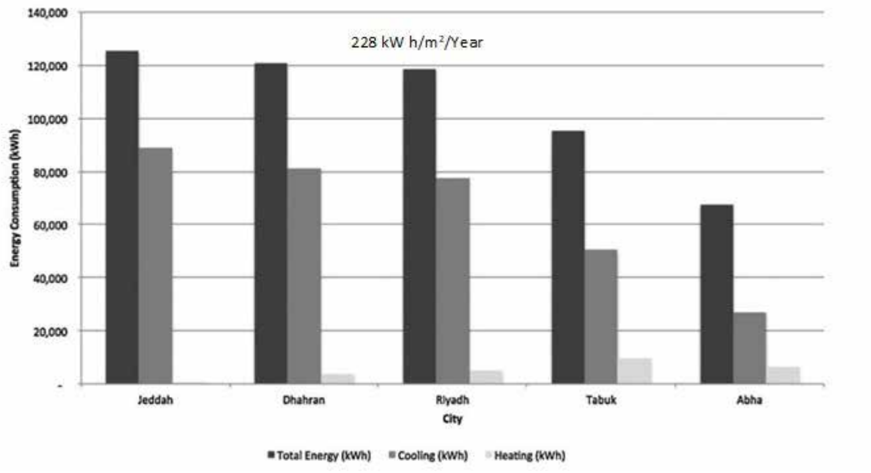

FIG. 2.5 Total annual energy consumption, space cooling and space heating for a villa located in five cities. Source: [29].

In Jeddah, the high cooling demand appears to be due to high temperatures and humidity that were reflected in the number of Cooling Degree Days (CDD), which is around 6587 °C -days (Table 2.1) [29], [39]. In the past, the energy performance of historic buildings was influenced by urban design, so the surrounding buildings controlled air movement and solar radiation, as shown in Figure 2.6 [56]. The building envelope acted as a storage buffer to store heat during the day and transfer it later, when needed, to the indoor space.

TABLE 2.1 Cooling and heating degree days for the five cities in KSA [29], [39].

City	Cooling Degree Days (CDD) (˚C-days)	Heating Degree Days (HDD) (˚C-days)
Jeddah	6587	0
Dhahran	5953	142
Riyadh	5688	291
Tabuk	4359	571
Abha	3132	486

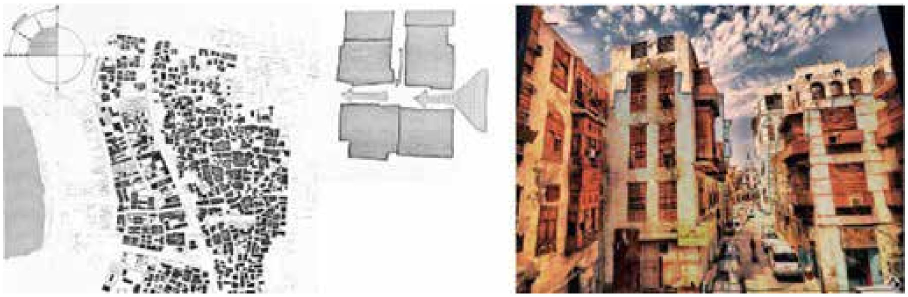

FIG. 2.6 Urban and air movement circulation in the historic district of Jeddah [29], [39].

Within the last five decades, the number of buildings in Jeddah has expanded rapidly due to population growth, from about half a million [57] to over four million [58]. Thus, the demand for housing and the fast growth of the population have driven the need for urgent construction of dwellings, illustrated in Figure 2.7 [59], which have avoided traditional building design values. This ignorance of traditional design values has resulted in buildings that depend entirely on AC systems. Moreover, human lifestyles and user comfort standards worldwide have changed, and in general, the need for cooling has increased enormously [60]. In 2018, the government implemented a new building code to ensure better energy performance of new buildings. As previously mentioned, the existing building stock results in massive energy consumption. Building designers need to investigate the leading causes of this high consumption and how existing dwellings can be refurbished for more efficient energy performance.

FIG. 2.7 New neighbourhood buildings in Jeddah [59].

2.2.2 Related Studies

A number of studies observed and examined the energy consumption of residential buildings in KSA [22], [31], [51]. The annual governmental report indicated that refrigerators use twice as much electricity as ACs in the average week [51]. However, the report did not demonstrate any energy measurement values that were able to be compared, such as kWh (Kilowatts times hour). A study by Aldossary et al. [22] that focused on residential buildings suggested that fundamental retrofitting improvements could generate a reduction of 37% in KSA residential buildings' energy consumption. A comparable study by Howieson [31] concentrated on how improving the building fabric performance coupled with ventilation ground pipes could lead to a decrease of approximately 80% in the cooling demands in KSA, achieved by adding a small chiller unit to a water reservoir. This research pointed to clear improvements that could be made without any fundamental enhancement of the building envelope. The solar radiation effect produces high cooling demands due to heat transfer from the building envelope. No earlier studies have considered user behaviour and its impacts on energy consumption. Unfortunately, the recent changes and developments in KSA are also not considered in these studies. Therefore, it is necessary to identify the leading causes of the high energy consumption of buildings.

2.2.3 KSA 2030 Vision Influence

The KSA government has prioritised sustainable measures as the gateway to a better future. As mentioned, the Saudi 2030 Vision was implemented in April 2016 [44]. Sustainability is one of the leading aspects of the Saudi 2030 Vision, and energy consumption is a critical indicator. The Saudi 2030 Vision states:

> “Our vision is a society in which all enjoy a good quality of life, a healthy lifestyle and an attractive living environment”. [44]

This specific aim illustrates an understanding of the necessity of a high quality of living but also respects the environment and considers future responsibilities. The government is taking serious steps to change the country's economy from an oil-based economy to a multi-source economy, starting with the 2030 Saudi Vision, which it intends to implement in all aspects.

In an endeavor to improve energy efficiency, the Saudi Arabian government has enacted a diverse range of policies and initiated various programs across multiple sectors, including industrial, land transport, and buildings. This thesis particularly concentrates on the building sector. Policy frameworks are formulated under the auspices of the Ministry of Energy, while the coordination and operationalization of the initiatives are managed by the SEEC where each initiative is categorized under a distinct program [61].

Concurrently, the electricity sector has undergone substantial transformation, marked by a series of regulatory, structural, and financial reforms. These changes are strategically aligned with the Kingdom's Vision 2030, highlighting the state's commitment to a more sustainable and efficient energy landscape.

In accordance with the established policies and strategies, the Ministry of Energy is responsible for formulating, endorsing, and overseeing the execution of development plans and programs within the sector. In its strategic planning for the energy sector, the Ministry of Energy adopts a comprehensive, multi-pronged approach [61]. Fundamental to this strategy is the reorganization of the sector itself, along with the incorporation of renewable energy sources into an optimized energy mix designed for efficient electricity production. A marked shift from liquid fuels to more sustainable forms of energy like gas and renewables is evident in these plans. Additionally, the Ministry is advancing the deployment of automation and intelligent grid technologies to ensure that electrical services are both reliable and efficient, all while reducing operational costs. Expansion of the national electrical grid to regions that are currently underserved is also a priority, and the Ministry actively seeks to engage the private sector in these initiatives, ensuring a commercially viable return on investment. In alignment with national objectives, there is a concerted effort to bolster local capabilities in the electrical sector through job localization and the support of research and development activities.

Moreover, the Ministry of Energy has initiated an array of specialized programs to further its objectives. These include the Optimal Energy Mix Program, designed to optimize the sources used for electricity production; the National Renewable Energy Program, aimed at expanding the role of renewables in the energy portfolio; and the SEEC, which focuses on promoting energy efficiency [61]. Additional programs such as the National Energy Efficiency Services Company Program "Tarshid," the Carbon Circular Economy Program, and the Sustainable Petroleum Demand Program have also been launched to address various facets of the energy sector's sustainability and efficiency.

In 2017, the International Energy Agency (IEA) [62] stated that KSA was targeting a 120-gigawatt electricity generating capacity by 2032 to accommodate the country’s electricity needs. Then, in 2018, the government decided to invest in renewable energy sources to cover the projected energy consumption for 2035. By July 2018, the KSA government announced a $200 billion investment to produce 200 gigawatts by 2030 using Concentrated Photovoltaics (PV) solar plants [49]. In November 2018, the National Committee of the Saudi Building Code (SBC) released the new building code to the public. The new SBC requirements and processing programs are intended to optimise new buildings' energy performance. However, the 5.47 million existing housing units [51] will still create massive cooling demand. To sum up, planning to promote alternative energy sources is essential. Nonetheless, knowing the causes of high energy consumption is critical to ensure holistic, sustainable future development.

In 2018, the building stock used about 80% of the electricity produced in the country see Figure 2.2, which has driven the government to enhance buildings' energy performance efficiency. Many reasons for the high current energy consumption have been put forward, including government subsidies, cheap electricity tariffs, a lack of building insulation, affordable AC units, the accustomed lifestyle, and the desire for a comfortable temperature range.

In 2018, the KSA government implemented several actions to avoid a future economic crisis due to high energy consumption, including a new SBC, activated SEEC, no longer subsidising services such as water, electricity and gasoline, and plans for renewable energy sources.

Notably, the decision to stop subsidising electricity has led to a slight growth in energy efficiency awareness, which is apparent when people compare energy prices. Energy users started to be aware of their electricity usage when the price per KWh increased by 260% from 0.05 to 0.18 SAR (0.013 to 0.048 USD) [63]. At the same time, a citizen account was created for a specific income range and launched to cope with the increased prices.

Current residential buildings need further developments to control and manage heat transfer through the building skin (envelope). There is a necessity to evaluate and assess current buildings' energy consumption in order to define the need for future developments. The recent changes concerning building energy consumption and user behaviour have not yet been investigated.

This research aims to explore and prove how the behaviour of users affects residential buildings' energy performance.

2.3 Research Approach (Methodology)

The research was based on a survey carried out using questionnaires in Jeddah City to assess current user behaviour regarding building energy consumption. The survey aimed to give a broad understanding of user energy behaviour and its effects on residential buildings' energy consumption.

The questionnaire focused on determining energy costs and user behaviour in light of the drastic increase in the price of energy. The survey formulated the questions as closed-ended questions. The survey targeted the householders (male or female) who were responsible for the energy bills. In December 2018, 396 completed surveys were gathered, which, considering an infinite universe, resulted in a 90% confidence level with a 5% margin of error. The research used Google Forms as a dissemination platform for the questionnaire after conducting, testing, and evaluating a pilot survey to ensure the validity of the questionnaire.

The survey was written in two languages: English, for the international public who lived in the area, and Arabic, the local language so that everyone could answer the questions. The survey design mandated that participants answer specific required questions before they could submit the survey, ensuring comparable results across all participants. Hence, it was impossible to know how many actual distributed surveys were attempted as the system automatically discarded the semi-/not-filled-in attempts. The survey was conducted in December 2018 using social media web-based links and an in-person link distribution in a shopping centre, The Red Sea Mall.

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2.4 Results

2.4.1 Demographic Profile

Three hundred and ninety-six completed forms were returned, equating to 333 respondents who actually lived in Jeddah; the rest lived outside of Jeddah. The survey results indicated that around 80% were Saudis, and the rest were expatriates. Most of the respondents were male (76.9%), and out of all the respondents, 70.6% were married. 44.1% of the respondents were between 20 and 34, and 39% were between 35 and 49. A total of 57.1% of the respondents held a bachelor’s degree.

Furthermore, the survey revealed that most respondents worked as an employee of the government (34.5%) or the private sector (36.6%). Table 2.2 elaborates on the demographic profile of the respondents.

More than 80% of the 333 respondents had lived in Jeddah for more than ten years see Figure 2.8; hence, it is assumed that they might have reliable information and understanding about the recent changes.

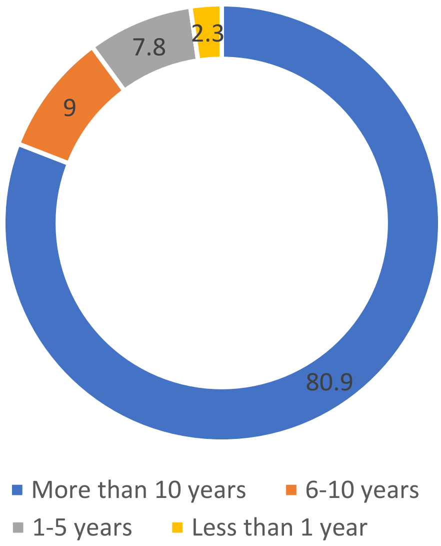

FIG. 2.8 Duration of living in Jeddah.

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TABLE 2.2 Demographic profile of respondents.

Respondents		
Total Respondents	396	
Respondents from Jeddah	*N* = 333	
Respondents	**% of Responses**	**Frequency of Respondents**
Residency Status		
Saudi	79.9	266
Non-Saudi	20.1	67
Gender	-	-
Male	76.9	256
Female	23.1	77
Marital Status		
Divorced/Widowed	0.9	3
Married	70.6	235
Single	28.5	95
Age		
Under 20	3.0	10
20–34	44.1	147
35–49	39.0	130
50–64	13.3	44
Over 64	0.6	2
Educational Status		
Incomplete high school education	0.6	2
High School education	18.0	60
Bachelor’s degree	57.1	190
Master’s degree	18.0	60
Doctoral education	6.3	21
Occupation		
Government	34.5	115
Business	10.2	34
Private sector	36.6	122
Retired	2.1	7
Unemployed	14.2	55
Household Size (number of people)		
Fewer than 3	9.3	31
3–5	43.9	146
6–9	39.9	133
10–16	6.3	21
More than 16	0.6	2

2.4.2 Income Levels

Figure 2.9 summarises the monthly income levels of the respondents in three categories: low income, average (middle income) and high income. Around 57% of the respondents fall above or below the national average income of around 2.6 K USD [64]. Low-income accounts for (23.1%) of the respondents (they belonged to the less than 1.3 K USD income group), and the rest of the respondents fall into the high-income group (salary above 8 K USD).

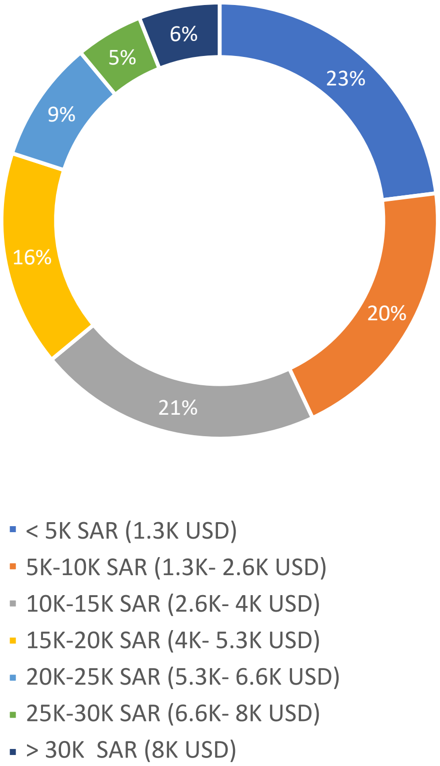

FIG. 2.9 Monthly income of respondents.

2.4.3 House Type and Ownership

The data revealed that about 64% of respondents reside in apartments and only 3% in independent houses. The remaining 33% of respondents lived in villas see Figure 2.10. The data revealed that more than 52% of the respondents owned their own houses, while 48% rented their abodes.
Furthermore, 14% of the households who rented spent above 30% of their income on rent; only 15% spent less than 10% (Figure 2.11).

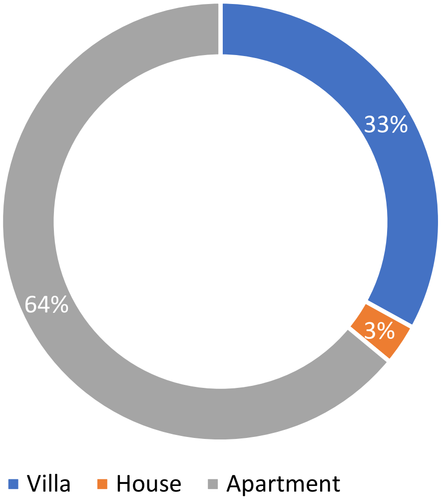

FIG. 2.10 Housing types.
* The pictures were taken from Google searches.

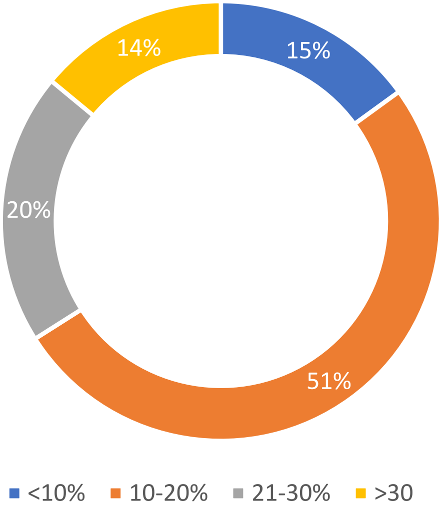

FIG. 2.11 Proportion of income spent on rent.

2.4.4 Energy Efficiency

Household energy efficiency is a significant concern for architects and other professionals working in the field of low-carbon buildings. Survey results indicate an optimistic scenario with lights and electrical appliances, where more than half of the respondents were using energy-efficient lighting appliances, including Light-Emitting Diode (LED) lights (45.9%) and Compact Fluorescent Light (CFL) lamps (12.9%). However, around 41% of the respondents still use a combination of energy-efficient lights and other essential appliances (Table 2.3). In fact, the users were open to other efficient strategies after they experienced such positive results with the efficient lighting strategy changes.

TABLE 2.3 Use of lighting appliances.

Lighting Appliances	% of Users	No. of Users
LEDs	45.9	153
CFL	12.9	43
Halogen	8.4	28
CFL & LED	6.6	22
Halogen, LEDs	6.6	22
Others	19.6	65

Thermal insulation was also an essential motive of energy efficiency plans. However, the survey results indicated that only 30% of the respondents reported that their houses were insulated, while 70% were not insulated (Figure 2.12). Therefore, upgrading the wall properties by adding proper insulation as a first step is an achievable possibility to achieve more efficient energy consumption.

Due to the hot–arid climatic conditions, air conditioning appliances are the primary items that increase electricity demands in Jeddah. Central AC and split ACs are more energy-efficient than AC window units and could reduce energy consumption by around 48% [65]. Figure 2.13 shows that 32% of the respondents used a combination of Split and window ACs, 8% used central AC, and 31% used Split ACs. 28% of respondents relied upon window AC units, which are less efficient. Hence, decentralised Heating, Ventilation, and Air Conditioning (HVAC) systems were widely preferred over central systems.

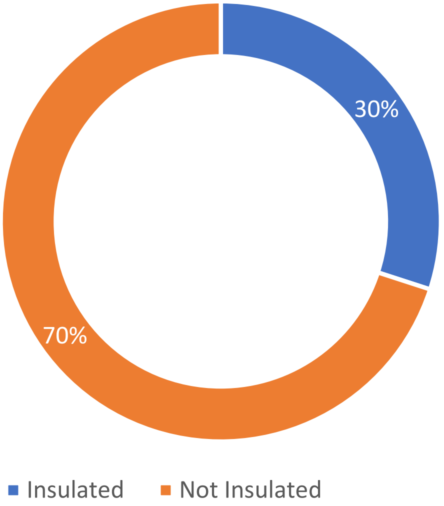

FIG. 2.12 Thermal insulation.

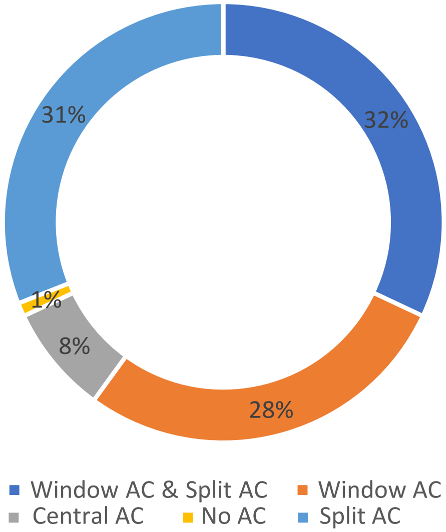

FIG. 2.13 Types of air conditioning.

Additionally, the satisfaction question included several variables better to understand a user's opinion of their home. The variables covered two aspects, namely, services and indoor comfort. The survey results revealed that respondents in Jeddah were satisfied with most of the building-level settings, services and amenities, such as room size (79.9%), water and sewer services (57.4%), water and sewer tariffs (64.9%), availability of daylight (72.7%), thermal comfort (64%), window ratios (72.7%), and outdoor acoustic quality (65.5%). However, the level of satisfaction was low (25.7%) regarding electricity tariffs (Figure 2.14). This was due to the recent 260% increase in electricity tariffs after the government stopped the subsidy of electricity tariffs. Remarkably, participants reported high levels of satisfaction with thermal comfort, which appears to be due to their preference for lower temperatures. This preference necessitates extended use of air conditioning in indoor spaces, as will be detailed in the subsequent figures. Central AC systems are not often used.

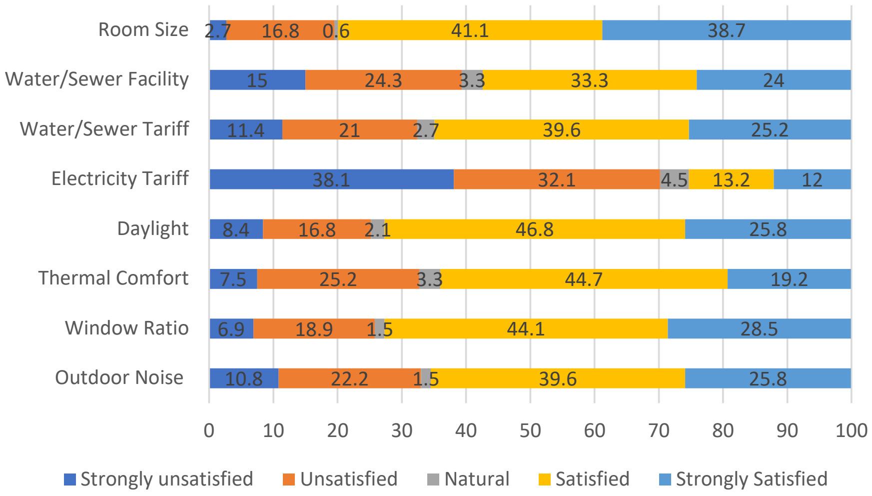

FIG. 2.14 Level of satisfaction in percentage on different variables.

Figure 2.15 also confirms that the majority of respondents (45.1%) preferred to keep their room temperature at 22–24 °C; 34.4% of respondents wished to maintain a temperature of 19–21 °C, and some respondents (8.1%) wanted to keep the temperature lower than 19 °C. Correspondingly, almost 80% preferred 19–24 °C due to the affordable electricity prices when using their AC units.

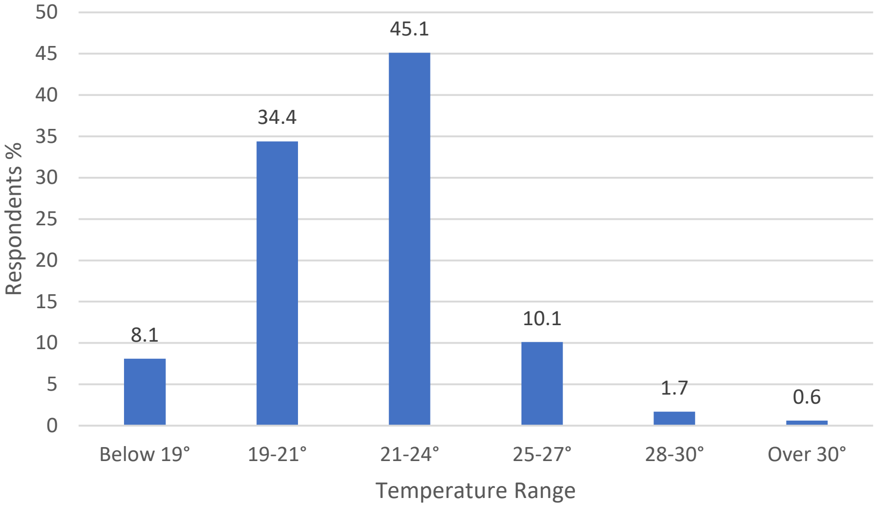

FIG. 2.15 Preferred indoor temperature.

The amount of time that the households use an AC unit daily also determines the electricity consumption. The survey showed that around 53% of households use the AC for more than 21 h. per day on average, and another 23% use it for 18–21 h. Only 9% of the households used the AC for less than ten h (Figure 2.16).
The Saudi government is trying to withdraw subsidies to reduce electricity and water use. The recent tariff hike was reflected by an increase of over 400% in the electricity bills of 13% of households (Figure 2.17).

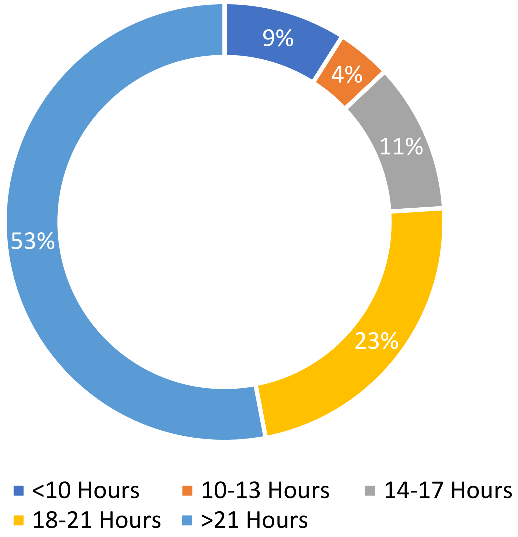

FIG. 2.16 Air conditioning (AC) use by households (in h).

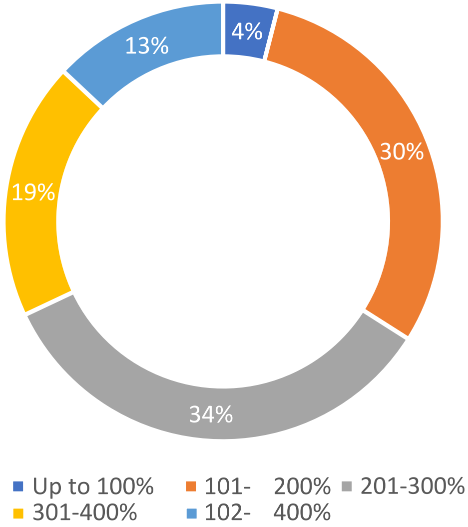

FIG. 2.17 Increase in electricity bills after New Tariff 2018.

It was observed that the increased electricity tariffs in 2018 significantly impacted household spending on electricity (Table 2.4). A total of 14% of the households surveyed had a less than 10% increase in their electricity bills. However, 62.6% spent around 20% of their income on electricity. Approximately 4% of households spent above 30% of their income on electricity, with the potential consequence that they must either compromise their savings or cut down their spending on other essential expenses to cope with the electricity bills.

TABLE 2.4 The percentage of income spent on electricity bills.

Spending on Electricity of Income	Number of Households
Above 30%	3.8%
20–29%	19.6%
10–19%	62.6%
Below 10%	14%

It was interesting to note how much a household spent on electricity per square meter of built-up area. Results revealed that 31% of households spent more than 5 SAR (1.33 USD)/m2 per month on electricity, while only 7% spent less than 1 SAR (0.26 USD)/m2 per month. A total of 62% of the households spent 1–5 SAR (0.26–1.33 USD)/m2 per month to cope with their electricity needs (Figure 2.18).

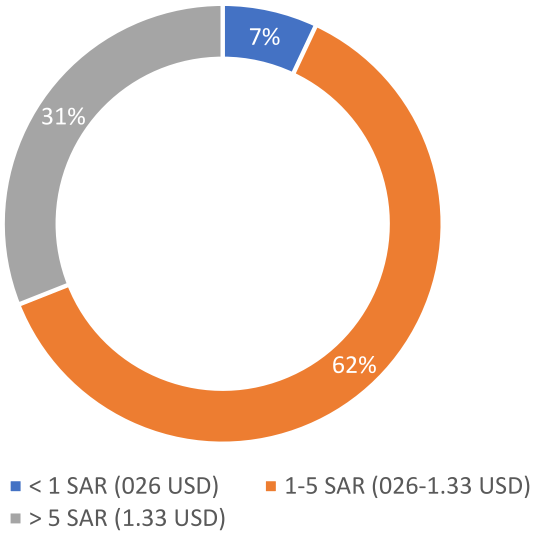

FIG. 2.18 Spending on electricity/m2.

2.5 Discussion

The focus of this study was understanding the causes of the high residential building energy consumption in Jeddah and the effects of users' behaviour on energy consumption. The study included different factors such as cost, user behaviour, and the buildings' thermal properties. The study tried to provide a broader understanding of the current energy consumption situation and lay a foundation for further energy assessments and possible solutions.

Though other studies had collected statistics for the same building types, the energy consumption was not explained, and the recent increase in electricity bills was not taken into consideration. Many researchers [13], [31], [66] showed that approximately 70% of the energy consumption was used for cooling the space. These researchers also recommended using better insulation in the building envelope for better energy performance. Furthermore, Hijazi [31] mentioned that any data outcomes from simulation software should be analysed carefully due to the expectation of errors. Aldossary [30] explained the difficulty of being able to afford utility bills.

Nonetheless, in their 2017 annual report [49], the General Authority for Statistics showed the average weekly usage of electricity per machine, which is not measurable regarding energy consumption. It would be more helpful if it reported the kilowatts per hour. The study findings explored a basic understanding of the energy consumption per square meter using kWh units. There is a need to retrofit residential buildings but to be able to do this, relevant information needs to be collected so that appropriate practical solutions can be decided upon and applied.

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2.5.1 User Behaviour

The results perceived as valid were based on the majority of households whose residents were educated (bachelor's degree or higher) and had lived in the area for more than 10 years. Just over half of the residents own their houses, and almost two-thirds live in apartments, partly due to the government-implemented Sakani (my house) program [40].

Due to the hot–arid climate conditions and poor building insulation, 70% of households have started to become aware of the benefits of insulating their homes. As a result, the massive cooling demand, which also corresponded to the daily use of ACs, increased electricity bills. Households maintain their thermal comfort by using AC systems extensively. This is due to many factors, such as poorly thermally insulated buildings, low energy prices, rising comfort standards, and the affordability of AC units. Air conditioning units are used for a very large number of hours per day. A total of 99% of households use AC systems, and two-thirds of these use AC systems for over 18 h a day due to the climate conditions and cultural aspects within Saudi Arabia. The head of the household's partner, young children, and/or the housekeepers spend most of their time in the house; therefore, houses are occupied continuously. Almost 80% of the respondents stated that their comfortable temperature range was 19–24 °C. The majority of households prefer temperatures below 24 °C.

Households have become aware of energy efficiency, as a study showed that almost half of households use LEDs. Hence, recently, the government tried to make the general public more conscious of efficient ways of using lighting and air-conditioning systems through various sorts of media.

Generally, households are satisfied with outside noise, window ratio, thermal comfort, available daylight, water tariffs, sewage tariffs, and room sizes. The users are also satisfied with their thermal comfort variable, using AC for long hours, but unsatisfied with the increased electricity tariffs. The increases in electricity tariffs were accompanied by other increases in tariffs, such as the 5% Value-Added Tax (VAT), sewer tariffs, water tariffs, and gasoline prices.

The government supports the increase in electricity tariffs and provides an assigned amount (based on income range) using the citizen account. The citizen account is a programme connected to every Saudi citizen who needs support from the government, which follows specific requirements and procedures. The government citizen account programme positively reflects respondents' satisfaction with the indoor comfort variables and the sewer and water tariffs.

Any retrofitting schemes, proposals, or designs should consider making the abodes naturally cooler and also consider implementing air conditioning units that are more energy-efficient, sustainable, run at a cheaper rate or can be supplied with cheaper energy sources.

User energy efficiency awareness is regarded as evidence to support the feasibility of introducing new retrofitting solutions. The households started questioning and analysing why their energy bills had increased and how they could reduce it. For example, around half of households upgraded their lights to LEDs in response to the government's announcement that it was increasing energy bills. However, there are opportunities for improvement in terms of building insulation, daylight, and efficient AC units to lower energy consumption. For example, there are techniques for improving energy performance, such as high-heat-resistant insulation, shading devices, and a seven-star AC labelling system. The study promotes retrofitting strategies on an individual scale. The study showed three income categories for the respondents; every category needs to be provided with a different solution and various levels of governmental support.

The energy efficiency awareness of households has increased, as reflected in the electricity bills. To illustrate, the study showed that one-third of households had their electricity bill increase by just 200% on average, while electricity tariffs had increased by 260% and had a 5% tax added to the bills. The study showed that approximately 53% of households had an increase in their electricity bills of between 200% and 400%. Notably, the increase in electricity bills affected the monthly percentage of income spent on electricity—now at 10–20% for approximately 63% of households. The money spent by Saudis on their monthly electricity bill is still lower than in many European countries such as Germany, Belgium and Denmark, where bills are in the range of 1–5 SAR (0.26–1.33 USD) per m^2 [67].

2.5.2 Energy Consumption Behaviours

The study results indicate that around two-thirds of households spend 1–5 SAR (0.26–1.33 USD)/m^2 (0.18 SAR (0.048 USD) per kWh) per month, which is a lower price than in Europe [67] but 260% more than what Saudis paid before the price hike. According to the survey, the biggest problem that households are facing is how to lower electricity costs by lowering energy consumption, especially after the increase in tariffs. Nevertheless, the government could face a future economic crisis if energy consumption stays at the same level.

In KSA, the SEEC mandated energy labelling of all electrical machines, which provides the energy consumption level to the buyers. The SEEC also offers efficient AC units at discount prices to the middle and lower classes, which can be paid in instalments. The building envelopes cannot maintain a constant cool temperature in indoor spaces for long periods. These observations indicate the necessity of developing the building envelopes' thermal properties. Then, active measures could be applied due to the high cooling demand in the hot–arid climate region. This could be achieved by architects redesigning the building envelopes to optimise energy consumption to keep the indoor temperatures naturally as cool as possible so that air conditioning systems can be kept to a minimum.

The study showed that almost every household uses AC units; this is reasonable due to the harsh climate conditions and the availability of cheap AC units. 91% of residences used individual AC units (window, Split), which could allow for individual retrofitting solutions. Thus, apartments can be redesigned individually to be more energy-efficient. Inevitably, individual options could affect the building envelopes' codes in the future.

All of the above findings point towards the necessity of retrofitting new buildings, which would affect the total urban energy design, gearing it towards being more energy-efficient and producing a more sustainable environment. The findings of the questionnaire also indicated that households within residential units became aware of the importance of their electricity consumption (energy efficiency) after the tariffs increased. In addition, buildings' thermal properties (heat transfer) need further improvements to achieve energy efficiency. To sum up, the existing residential buildings in Jeddah were designed based on the affordability of AC units and subsidised energy bills, which resulted in poor thermal building designs and high energy consumption. Thus, improving existing buildings ought to come through enhancing the thermal properties of the building envelopes (roof, wall, windows and floors) and then applying proper active measures on a case-by-case basis.

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2.6 Conclusions

This chapter aimed to assess how current user behaviour affects the energy performance of residential buildings in Jeddah. The results indicated clear opportunities for enhancing the building envelope by upgrading its thermal properties. This includes consideration of related factors such as building materials, insulation, and shading devices, etc. Nonetheless, increasing user awareness is also essential for developing more sustainable solutions. Despite the increase in electricity tariffs, households still use their AC units for long periods since they spend a significant amount of time in their homes. However, households will not accept any solution resulting in indoor temperatures above 25 °C as indicated by Felimban [41].

The survey results enhanced our understanding of the current state of energy performance and related electricity consumption costs in residential buildings. These findings are consistent with literature that includes statistics from other hot-arid climate countries such as the USA, Kuwait, Oman, and the UAE. The data suggests that 70% of existing residential buildings require insulation upgrades, and it remains unclear whether buildings with insulation are properly designed. High energy consumption in residential buildings is primarily due to the use of air conditioning systems and the length of time they are operated. Moreover, users expressed dissatisfaction with rising electricity tariffs, even though they remain relatively low compared to those in Europe. These results emphasize the necessity for energy upgrade measures, along with a related cost-benefit analysis, which will be explored in subsequent chapters.

In brief, short-term solutions to improve building energy performance are necessary to ensure sustainable plans and efficient energy use. The published results indicated that several factors impact the energy consumption of residential buildings [41]. First, new residential buildings' thermal properties were found to be poorly designed. Second, the majority of users prefer a room temperature below 24 °C, which requires a massive amount of cooling. Third, due to the climate conditions and the typical lifestyle of KSA, housing units are occupied for more than 18 h per day. Fourth, increasing user awareness has helped slightly improve residential buildings' energy efficiency.

Existing housing units consume massive amounts of energy and require further detailed investigation into their energy performance, energy costs, and the effect of user behaviour on energy. Formulating a set of architectural redesigning (retrofitting) parameters is necessary for self-sustainable buildings.

2.7 Limitations

It would have been challenging to produce more detailed questions for the survey regarding energy consumption. The type of electronic questionnaire that was used was limited as it only recorded complete questionnaires; partly completed questionnaires were disregarded. It was also not possible to determine, in detail, how the household's electricity was consumed, such as for cooling, heating, cooking, cleaning and ironing. Extra information regarding the energy levels of AC units, LEDs and other machines would have helped define the energy rankings of these appliances.

3 A Framework for energy upgrade

Using energy retrofitting strategies scenarios for mid-rise residential buildings envelope in hot-arid climates: The case of Jeddah, KSA

The previous chapter clarifies the need for energy retrofitting investigation for residential buildings in KSA; therefore, this chapter identifies a set of parameters (cultural background, existing energy retrofit (levels and strategies), energy performance challenges, Jeddah Climate, building stock, construction method, materials, design parameters and KPI's) to propose potential energy retrofitting scenarios for residential buildings. The aim is to define the context of energy retrofitting in KSA using Jeddah city, which acts as a framework for proposing possible energy retrofitting scenarios.

The first section of chapter three introduces the recent governmental acts and the study focus. Then the methodology section followed to illustrate how the study designed the chapters. Then the background review section discusses the cultural background and cost of living changes, literature review (Retrofitting strategies and levels), energy performance challenges, and Jeddah climate challenges). Then an overview of the existing residential stock section is presented, followed by the design parameters and KPIs section. The previous sections set a framework for section 3.6 of available energy retrofitting upgrading possibilities. The conclusions section presented possible energy upgrade scenarios that need further validation.

3.1 Introduction

The KSA faces a significant challenge, with buildings consuming 75% of the country's total electricity, with air conditioning systems accounting for half of that consumption. This energy demand is projected to exhaust all oil exports by 2035, which could lead to an oil crisis [7], [43], [49], [68], [69]. To address this challenge, the KSA has initiated various programs to reduce energy consumption and support the goals of the 2030 Saudi Vision, including upgrading building codes for new constructions and implementing energy-saving measures [44]. However, there is an urgent need for energy efficiency upgrades to existing buildings, particularly the 5.5 million residential housing units, to achieve the Saudi 2060 Net Zero target [70]–[72]. The previous chapter's findings highlight the importance of implementing energy upgrade measures, particularly concerning electricity consumption, which involves building performance and user behaviour [41]. Therefore, energy efficiency upgrades to the existing housing units are necessary to meet the current minimum energy standards of the Saudi Building Code (SBC).

This chapter intends to formulate a solid ground which leads to the next chapter of the study showing how KSA wishes to increase the efficiency of the existing residential building energy performance to the maximum to at least meet the upgraded minimum SBC energy standards. Although energy efficiency is not the only motivation to promote applications for energy retrofitting measures, cost-saving is a critical driver that encourages building owners to accept, invest in and implement the retrofitting measures, especially with the rapid increase of the recent cost of living due to increasing energy prices.

House owners are often unaware of how to lower their building energy consumption on a building scale. In most cases, the energy bills are still payable; thus, the existing housing owners are not motivated to upgrade their energy efficiency [41]. However, with a future prediction of energy costs increasing significantly, the energy price would become too overpriced for homeowners, resulting in unpayable energy bills. Therefore, informing the residents of the importance of energy upgrades is a means to improve the building's energy performance with appropriate saving measures for maximum efficiency, which would help to lower the amount of energy used and the energy bills in the long run.

In July 2021, the updated SBC regulations were introduced to promote the construction of new residential buildings that offer significant energy savings. However, in October of the same year, the SBC National Committee revised some of the initially established standards due to concerns expressed by architecture firms, resulting in very few, if any, building construction permits for at least three months[73].

As more than 70% of existing residential buildings in 2022 still have defective energy performance, they must be upgraded with suitable energy upgrading measures to lower the KSA total energy demand. Due to this, social benefits needed to be created, including creating new job opportunities within the energy retrofitting market and improving building indoor space quality.

The main problem is the building design which needs a design framework to limit the study scope and support reaching significant energy savings solutions. Therefore, Chapter 3 aims to build up a solid ground base for designing potential energy retrofitting scenarios for existing residential buildings using Chapter 3 as a design framework of potential energy retrofitting case models for residential buildings (mid-rise) in Jeddah City. The framework illustrates the challenges of upgrading the energy performance of the residential buildings in Jeddah, considering its users and the climate. The scenarios show available energy upgrade possibilities to enhance the building energy performance levels, which intend to meet the upgraded SBC energy standards. Hence, the framework presents the recent retrofitting strategies in (research and practice), the cultural background, the energy efficiency update and the materials available within the Jeddah context. Also, the leading Key primary indicator, kWh/m2 per year, has been used to evaluate the proposed scenarios, which have been presented later in the chapter. The following chapters have selected, assessed, and evaluated the most promising designs regarding energy and cost.

The study has focused on Jeddah city for various reasons. Initially, the challenge of the hot-arid climate in Jeddah currently requires a greater cooling demand of approximately 6,587 CDD compared to other cities Dhahran, Riyadh, Tabuk, and Abha (5,953, 5,688, 4,359 and 3,132 CDD)[29]. Also, the Makkah region (where Jeddah is located) contains the highest number of apartments (multifamily buildings) compared to the other regions in KSA [32]. Therefore, significant energy savings are expected when novel scenarios are defined.

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3.2 Methodology

The study presented a framework for designing envelope energy upgrade scenarios for residential buildings in Jeddah that utilize appropriate retrofitting strategies to enhance energy efficiency. The chapter was structured into four parts to ensure coherence and utilizes a mixed-method approach, incorporating qualitative and quantitative methods to provide current knowledge and information. The first three parts used qualitative methods using the state of the arts and literature review to establish a foundation for the fourth part. The fourth part employs qualitative and quantitative methods to illustrate possible options for energy retrofitting measures.

Initially, Section 3.3 provided a background review that covers different sub-sections such as the cultural background, cost of living, literature review, related studies, and current practices in KSA and similar contexts to identify knowledge gaps in energy-retrofitting measures for existing buildings in KSA. The chapter also discusses various energy retrofitting strategies available for KSA and outlines a retrofitting classification system appropriate for the KSA context. Additionally, Section 3.3.1 addressed energy performance and climatic challenges in Jeddah, considering technical, cultural, economic, and environmental aspects. The section limits the study scope to the Jeddah context by providing an overview of the residential building stock, and data was collected from previous studies and local business sources through various means of 1communication, including website reviews, email discourse, social media accounts, and telephone calls.

Section 3.4 presented an overview of the existing residential stock in Jeddah, including a discussion of residential types and trending types based on recent stock growth. The section highlighted changes in building construction regulations at the general level to justify the development of building/unit ownership, and typical construction methods and available materials such as block, insulation materials, wall finishing, windows, and sealants are also discussed to identify available materials that could be used in energy upgrade scenarios.

Section 3.5 identified the design parameters and KPIs for Jeddah city to meet upgraded SBC standards. The section established different design parameters from the literature and previous chapter results and specified the main KPIs to be used in the thesis.

Section 3.6 outlined various possible technical scenarios and identified the available scenarios based on data collected in the previous sections, including information about U-Values and R-Values as they are the primary indicators of envelope energy performance enhancement. The study also emphasized that the infiltration rate indicator can significantly impact energy efficiency performance. The chapter's central concept was to provide possible upgrading options for each targeted building component. Besides, Figure 3.1 illustrates the chapter steps outline.

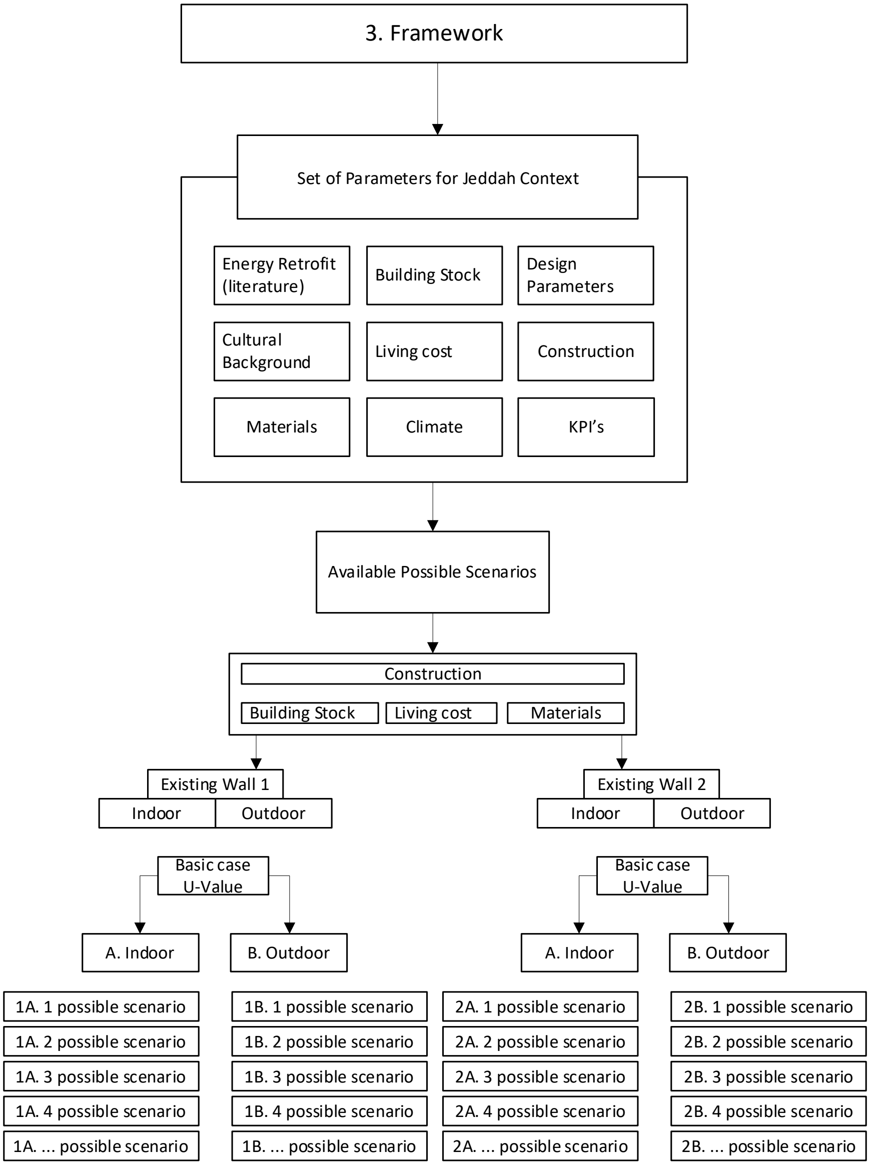

FIG. 3.1 Chapter 3 outlines overview.

3.3 Background Review

3.3.1 Cultural Background and Cost of living changes in KSA

Saudis lifestyles differ significantly from European and American lifestyles. The average Saudi family size is larger than the European and American family sizes, and everyday activities are dissimilar to the mentioned lifestyles. Typically, a Saudi family has six members and a live-in homemade[30]. The primary source of income is from the husband, and only occasionally does the wife work as well. The husband is obligated culturally for any financial needs. The residents occupied the house usually most of the day, especially if the wife is unemployed.

In the earlier chapter, Felimban- et al. noted that the average working hours for the air conditioning unit is above 18 hours per day, and the comfort temperature ranges between 19-24°C [41]. The same study also showed that 99% of the households used AC systems and illustrated that 70% of the residential buildings were not thermally insulated [41]. Surprisingly, in another study, Yousefi said that it was possible to make enormous changes of up to about 90% of the heating and cooling demands if the interaction between occupant behaviours and envelope materials selection were considered [74].

However, the building householders were unaware of the current energy consumption level until the cost of living increased in 2018. Subsequent to the implementation of recent economic policies by the government, including hikes in utility tariffs for electricity and water, as well as a rise in gasoline prices, a decrease in government subsidies, and an upsurge in Value Added Taxes (VATs), users have encountered difficulties and expressed dissatisfaction with their monthly electricity bills, as highlighted in the preceding chapter.

In fact, since January 2018, the cost of living expenses has increased significantly in KSA. Initially, the electricity tariff prices increased by 3.8 times as a saving measure to improve the users' awareness of the energy consumption towards lowering the country's total electricity demands. The electricity tariff had four categories and was later upgraded to two types, as described in Table 3.1. The building householders were shocked by their new monthly electricity bills, which increased 3-4 times what they had previously paid. Interestingly, after the last increase, the recent electricity tariff in KSA is approximately one-third of the average European Union (EU) electricity tariff, about 24.4 $ cents per kWh, as shown in Figure 3.3.

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Secondly, water tariffs were also increased and evaluated with different prices per m³, as illustrated in Table 3.2. Moreover, the sewer services were added to the water bill costs when the building owner connected the sewer pipelines to the main sewer pipeline. Thirdly, gasoline prices have also increased several times over a short period. Recently, the energy ministry linked the monthly gasoline prices to the oil world prices by removing the governmental subsidies see Table 3.3 and Figure 3.2.

TABLE 3.1 Electricity tariff cost changes (2016-2018) [3]

Before 2016 (kWh)	US $ Cents	2016 (kWh)	US $ Cents	2018 (kWh)	US $ Cents
≤ 2000	1.35	≤ 2000	1.35	≤6000	4.86
2001-4000	2.7	2001-4000	2.7	>6000	8.1
6001-7000	3.24	4001-6000	5.4		
6001-7000	4.05	> 6000	8.1		
7001-8000	5.4				
8001-9000	5.94				
9001-10000	6.48				

TABLE 3.2 Water tariff prices changes (before and after 2016) [75], [76]

Before changes (U.S. $ cents)	Water tariff per 1m²		After2016 changes (U.S. $ cents)
0.027	≤50	≤ 15	0.027
0.0405	51-100	16-30	0.27
0.54	101-200	31-45	0.81
1.08	201-300	46-60	1.08
1.62	More than 300	more than 60	1.62

TABLE 3.3 Gasoline Prices in KSA from 1995 to 2020 [77]

Actual	Previous	Highest	Lowest	Dates	Unit	Frequency
0.43	0.38	0.58	0.12	1995 - 2020	USD/Litre	Monthly

FIG. 3.2 Gasoline Prices 2012-2020 [77]

The finance ministry also minimized the governmental subsidies for most energy products used to subsidize. The ministry initiated alternative financial support such as the Citizen account and high-cost living allowances. The Citizen account was initiated for Saudi families who needed help to cover the increases in living expenses based on their yearly income. Lately, the government has terminated the high-cost living allowance because of the COVID-19 situation to move this money towards the healthcare systems.

Furthermore, 5% Value Add Taxes (VAT) were added for the first time in the KSA history, negatively reflecting the market sales and the cost of living. Recently, the VAT increased to 15% due to the COVID-19 precautionary application measures as part of the country's economic recovery plans. In addition, other products have increased in price by adding different percentages of selective taxes based on specific criteria that could negatively affect the citizen´s health in the long run, such as tobacco products, energy drinks, sparkling drinks, and sweet drinks.

Currently, households and KSA residents face an enormous increase in their cost of living, especially electricity bill costs, primarily caused by the energy performance defective of existing housing units. Therefore, this study has indicated possible scenario interventions of energy upgrades through retrofitting activities to enhance the energy performance of the current housing units in the Jeddah context.

3.3.2 Literature Review

This sub-section highlights the knowledge gap from the previous studies of energy retrofitting upgrades and the latest methods used in the field. Also, related studies and existing practices have been presented in this sub-section.

Many researchers have investigated the advantages of energy conservation measures for residential buildings in the Gulf Cooperation Council (GCC) countries. Nevertheless, the recent increases in the cost of living and the government's vision of energy conservation measures have not been investigated, especially in the KSA context. KSA citizens have only recently been given knowledge and basic information about energy savings and conservation measures. Several studies have shown that it is possible to obtain remarkable savings in energy consumption when applying different saving measures in several ways. Yet, the various costs were often not explicitly taken into consideration in the majority of the studies.

Similarly, several researchers such as [13], [78], [79] have reported diverse energy savings ranging from between 15%-72% when implementing different saving measures such as insulation upgrading, U-value upgrading, window glazing upgrading, electrical devices upgrading, installing shading devices and installing on-site energy generation units. Konstantinou showed five specific strategies (replace, add-in, wrap-it, add-on and cover-it) that could be included in any refurbishment design of ageing residential buildings to provide a toolbox for refurbishment strategy possibilities that assist the decision-making processes [34].

The main result was providing the facade refurbishment toolbox to support the design process's decision-making. To clarify, all provided strategies around improving all building envelope components where heat loss occurs (for both the inside and outside of the buildings). In contrast, in the KSA context, the energy retrofitting strategies aim to improve all building envelope components where heat penetrates (specifically from the outside of the building to the inside of the building) due to the KSA context.

Various researchers have reported different energy-saving measures considering climate and economic conditions in GCC countries. These studies have provided a base knowledge showing which strategies could be applicable and feasible elsewhere and may be applied within the KSA context. Yet, the unexpected increases in the cost of living and other economic factors, such as adding VAT and increasing or adding new service fees, need further investigation.

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For instance, in Kuwait, research in 2003 showed savings of 3.25 million MWh over ten years when applying savings measures such as insulation, glazing upgrade and lowering the window area, which targeted 42,403 old residential buildings retrofitted [17]. The main challenges in this project were that the Kuwaiti government was the main financer of the initial costs of the retrofitting measures, and the payback period was over 30 years, during which the electricity tariff prices continued to be subsidised. Furthermore, Krarti presented the economic and environmental benefits of improving energy efficiency for new and retrofitted Kuwait buildings [80]. The study recommended three levels of retrofitting proposals for better energy efficiency. Also, the research showed that using different energy savings measures could reach 8%, 23% or 50%.

Similarly, Krarti et al. recommended similar implementation measures for KSA buildings to achieve comparable energy savings but on a larger scale. In addition, Ameer suggested that doubling the electricity prices (electricity tariffs) in Kuwait would incentivise the implementation of energy efficiency measures for the residential buildings sector, which would, in turn, benefit the Kuwaiti government [81]. In conclusion, Kuwaiti building users currently depend on government subsidies for their energy bills, similar to all of the GCC countries, but the amount of subsidies varies depending on the country.

In contrast, in the UAE, Taleb [18] tested upgrading building thermal performance using eight passive cooling strategies to reduce the energy consumption of up to 23.6% in residential buildings in Dubai [18]. Also, Alfaris explored remarkable efficiency in energy performance by 25%in average when applying low and medium energy conservation measures[14] [78]. It resulted in energy consumption savings between 14.4% to 47.6%, depending on the individual operating conditions and the occupants' behaviours. Rakhshan showed a 40% reduction in the summer peak demand and a 32% reduction in CO2 emissions after improving wall insulation to a U value of 0.3 W/m^2K by upgrading the AC systems to a Coefficient of Performance (COP) of 2.7 [23]. Giusti et al. explored occupants' behaviours on electricity consumption when they raised the AC thermostat temperature to 24°C by switching off the domestic water heating when it was not needed and adding roof insulation which all affected different percentages of savings concerning energy consumption [82].

Friess et al. reviewed several passive measures such as building orientation, thermal insulation, appropriate glazing types and orientation, excessive light levels and glare, and natural ventilation that were able to save energy consumption by 30% in Villas and up to 79% in high rise office buildings [83]. Studies on saving measures have been explored more in the United Arab of Emirates (UAE) than in other GCC countries, showing different results that have lately been applied.

On the other hand, building user behaviours regarding energy savings have a significant impact, as several researchers have illustrated. Al-Saadi showed a substantial reduction of up to 42.5% in annual energy consumption; they researched the calibrated model of a typical house in Oman using several saving measures [84]. Alalouch pointed out an urgent need for large-scale retrofitting programs, which could significantly reduce energy consumption using suitable energy savings measures [27].

Aldossary proposed various management and technical upgrades in KSA that could serve as a benchmark for enhancing energy efficiency in the country's residential stock. The author identified three prototype houses that exhibit maximum energy efficiency, surpassing international standards. These recommendations are considered exemplary standards for implementing retrofitting measures in KSA's residential buildings in the future. On the same topic, Krarti explored optimal energy savings for residential buildings that ranged between 26%-47.3% in five, unlike sub-climate zones in KSA [29]. The savings occurred when applying energy conservation measures on building envelope elements such as wall insulation, roof insulation, window area, window glazing, window shading and the thermal mass centred on the life cycle cost and energy savings [29]. Additionally, Alaidroos pointed out that applying energy conservation measures within the KSA region could lead to significant annual savings on energy cost subsidies, national oil consumption and investment in new power plants [29].

Also, Alaboud noted that there could be a substantial decrease of around 35% in the cooling load by using the necessary measures such as reducing Window to Wall Ratio (WWR) from 15.3% to 5%, adding insulation to the roof and the external walls and increasing the thermostat temperature in the houses by 1 °C [85]. The study suggested that if the necessary measures were implemented, it would result in a 35% reduction in the cooling demand, which could be higher if other retrofitting plans were applied, considering cost-effectiveness. In 2019, Krart showed that retrofitting residential buildings could reduce energy consumption by as much as 60% [86]. Also, it could help to generate energy that could be only used for the buildings or returned to the grid by using Solar Panels (PVs) on the building's roofs in KSA [86]. The previous studies explored different strategies in energy-saving measures centred on the building's energy performance.

To sum up, the studies showed a significant impact in energy savings ranges between 15%-72% when applying different energy retrofitting measures that use the appropriate combinations of saving energy interventions, as Table 3.4 illustrates. Unfortunately, the previous studies have not considered the recent changes in the KSA context, such as recent energy cost increase, building code update, and the government development towards the 2030 vision, which is where the knowledge gaps currently exist.

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TABLE 3.4 The Strategy Types and The Savings Interventions

Strategy Type	Replace	Add (inside)	Add (outside)
Envelope energy-saving interventions	Wall filling (blocks)	Wall filling (blocks)	Shading Devices
	Insulation	Insulation	On-Site Energy
	Air Sealant	Air sealant	
	Window	Window	
	A.C. Systems		

3.3.3 Retrofitting Strategies for mid-rise residential buildings in Jeddah KSA

Different factors influence any energy retrofit application, such as micro-climate, thermal properties of building fabric, occupants' thermal comfort level, owners' acceptance of changes and economical budget [84]. However, a study by Ma emphasised that sustainable energy retrofitting applications must follow a strategic design process that requires careful decision-making processes at different phases [28]. The same study showed a systematic approach to achieving sustainable energy retrofit application for buildings which can be divided into three activities: pre-retrofit (possible solutions), retrofit (testing), and post-retrofit (evaluate the application) [28]. Similarly, energy retrofitting strategy applications require similar processes to get an appropriate application for maximizing energy efficiency.

Energy retrofits can be categorized in many ways [88]–[92]. Natural Resources Canada (NRCAN) categorized retrofit activities into three scales: minor retrofit, major retrofit, and deep retrofit. The thesis uses the NRCAN categorisation as a baseline [88]. The scales were classified based on the intervention level of the changing activities and the energy savings percentage.

A The minor energy retrofit

A minor energy retrofit is considered an easy upgrade to implement for a low-cost investment. It includes fixing the gap in the sealing, implementing lighting upgrades, making electrical device upgrades, adding a controlling system, and regular maintenance. These activities need small interventions with a no/low disturbance for building users.

B The major energy retrofit

A major energy retrofit includes appropriate changing or upgrading activities to lower the building's energy consumption while entailing only a tiny disturbance for the building's user(s). Significant energy retrofitting activities include replacing, upgrading or adding building elements such as windows (frames, pans, pan cavities, glazing), wall thickness, insulation, shading systems, gap filling and more efficient AC systems.

C The deep energy retrofit

In the long run, a Deep Energy Retrofit (DER) achieves considerable energy savings, which could reduce energy costs by up to 60%.

The International Energy Agency (IEA) defines Deep Energy Retrofit (DER) as:

> "A major building renovation project in which site energy use intensity (including plug loads) has been cut by at least 50% compared to the baseline with a corresponding improvement in indoor environmental quality and comfort"[93].

In the same study, the Deep Energy Retrofit is a comprehensive approach for any upgrades, adding or changing the building systems that could achieve at least 50% savings in energy consumption costs. This activity considers all of the major activities that possibly cause major disturbances for the building user(s), such as replacing the entire façade, adding a second skin façade or adding an External Insulation Finishing System (EIFS) as insulation cover.

The different levels of interventions and activities are illustrated in Table 3.5, which explains what could be changed at various energy retrofit measures.

TABLE 3.5 Main differences between minor, major and deep energy retrofits.

Minor	Major	Deep
Lighting Upgrades	Windows (Frames, Pans, pans cavity, Glazing)	Major energy retrofit activities
AC systems Upgrades		Outdoor Insulations (EIFS)
Electrical Devices Upgrades	Wall (Thickness, materials)	Second Skin Facades
Gaps fillings fixes	Insulation	Replace the Entire Façade
Electrical Devices Maintenance	Gaps filling	
Controlling systems	Shading systems (fix, Active)	

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In this study, the energy retrofitting definition is any changes (replacement, repairs, upgrades or additions) that increase the building's energy performance efficiency and lower energy consumption costs. The scope focused on the possible energy retrofitting strategies and their benefits economically and environmentally.

Initially, in KSA, the concept of energy retrofitting strategies was not recognized among building users due to the low energy tariffs. Still, attitudes and approaches changed when the tariffs increased by around four times, as mentioned earlier. The Social Development Bank) SDB([94] in KSA defined the restoration loan/finance as:

> "A financing program designed for restoration, maintenance, repair of structural and emergency defects, for the purpose of additions or necessary modifications for private residential houses". [94]

Until recently, energy retrofitting measures were not involved in most of the professional architectural practices in KSA, but things are changing, and this is becoming more standard practice as it is becoming more important to the clients. The new increases in energy prices and the definition of a building's energy performance defects have changed and are currently being more closely monitored.

It is interesting to note that the competitive energy prices in KSA are still lower than the average energy consumption prices in European countries, as shown in Figure 3.3.

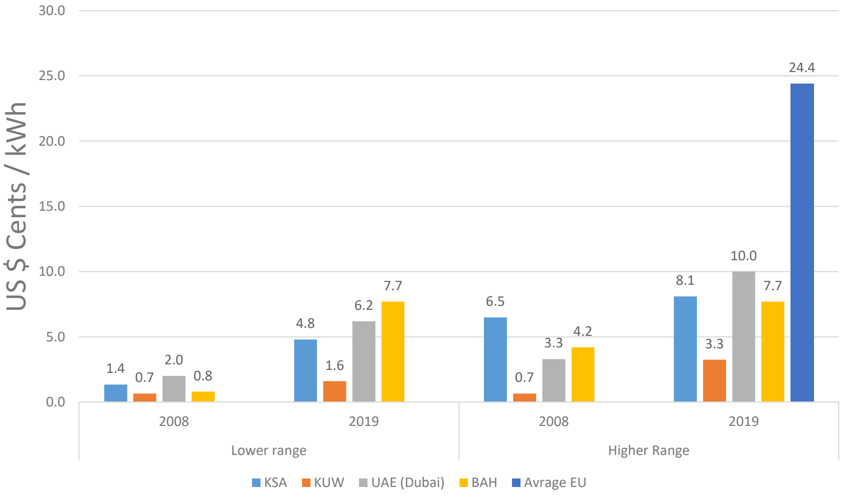

FIG. 3.3 Electricity tariff prices comparing four GCC countries and the EU.

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SEEC initiatives have to a large extent, covered minor energy activities, such as providing several programs encouraging the labelling of electrical devices (including the lighting and the ACs) and providing efficient AC discounts. They have increased public awareness of energy efficiency through the media. Nevertheless, the major and the deep energy retrofits have not been comprehensively covered by the SEEC.

Energy retrofitting strategies in the KSA context have received a low acceptance rate in general from householders due to many factors, which have included in the past the high initial costs and the low interest among users of energy efficiency; this was mainly because of the low energy tariffs, as shown in Figure 3.3.

In the past, any energy retrofitting solutions needed to consider the initial costs of the buildings' energy improvements compared to the current scenario, emphasising the total energy savings and its potential effect on the energy cost. Hence, energy performance and cost are primary indicators for evaluating energy consumption levels.

The challenge is to create a comfortable indoor space for building users whose indoor temperature ranges between (18°-24°C) within the harsh outdoor hot desert climate that yearly has high peaks ranging from between 32° to 49°C. (Jeddah) [41].

Despite the limited number of residential building renovation projects in KSA, energy upgrades have not been a significant consideration, even among existing projects that have not met upgraded SBC standards. Homeowners typically renovate their buildings for aesthetic or structural purposes, with little emphasis on energy efficiency. However, a recently documented renovation project of a residential building serves as an example of incorporating energy upgrade measures alongside aesthetic improvements, resulting in substantial energy savings. This case highlights the common misconception that residential building renovation is solely for aesthetic purposes and emphasizes the importance of considering energy efficiency measures during renovation projects.

Austah House is a recent renovation case carried out in Yanbu city, western region, KSA, representing a real opportunity to see what energy enhancement possibilities are available see Figure 3.4. The following information is based on an interview with the owner and architect (Moaad Austah) and with using Twitter (a social media application) for supporting pictures and information [95].

The main reasons for renovating the Austah house were based on cultural aspects, building quality and economic aspects, which shows how building owners approach renovation activity, as shown in Figure 3.4. The building construction took two years and was finished in 2020. It took so long as the building was inhabited while working on the construction.

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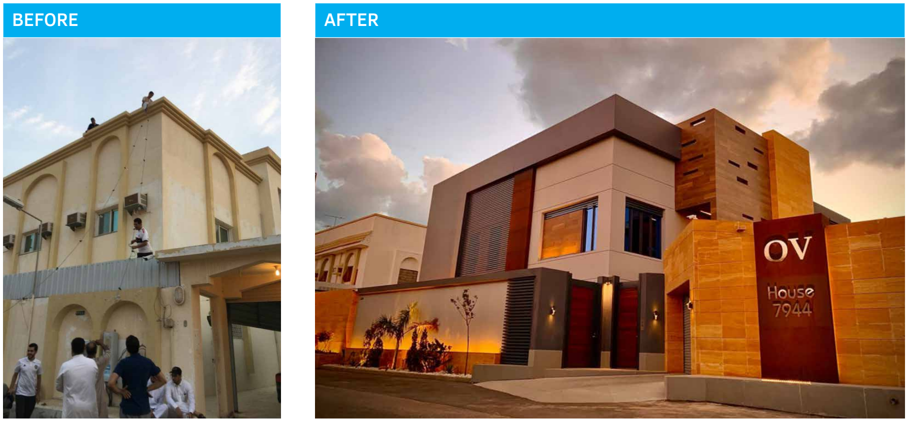
BEFORE

AFTER

FIG. 3.4 Austah House’s recent renovation project in Yanbu City, KSA.

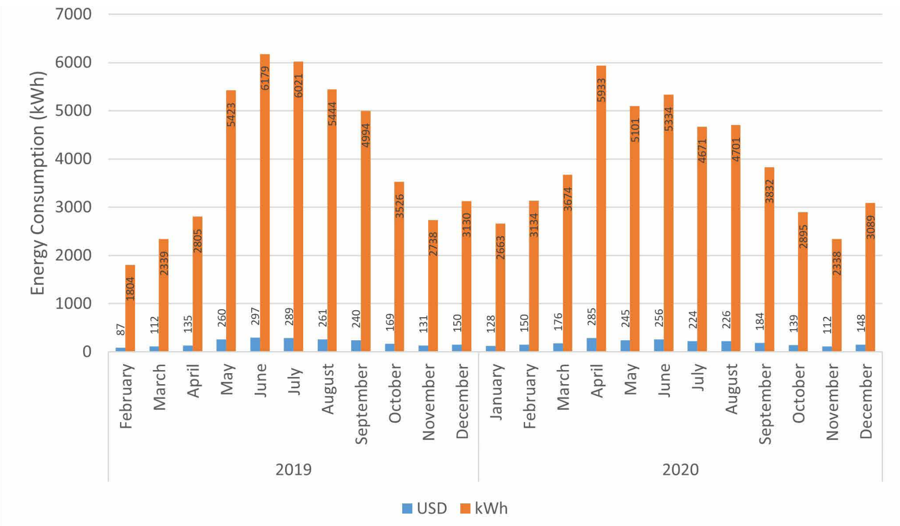

FIG. 3.5 2019-2020 energy consumption and energy cost for 1st floor.

The main changes incorporated into the house regarding energy-related elements included upgrading the walls, the windows, the lights and the ACs. The east and west facade walls were upgraded with a 15 cm (centimetres) block, 5 cm insulation panels, 15 cm block, and 2.5 cm of mortar on both sides of the wall, resulting in a 40 cm wall thickness. Also, the windows were upgraded with double-glazed windows within a frame with a thermal breaker (6mm glass, 12mm air vacuumed and 6mm glass). 18 AC window units were replaced with splitting AC units with five or six stars energy efficiency levels. The owner claimed that there was a 30% energy saving that occurred after the building renovation.

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The study observed the monthly electricity bills to identify the actual energy consumption. Two years of energy consumption from February 2019 to December 2020 were observed. The first-floor average energy consumption was around 135 kWh/m² per year, and that energy cost was around 24 S.R. (US $ 6.4), as illustrated more in detail in Figure 3.5. The Austah house case illustrated diligence on renovation, including some energy retrofitting measures such as (wall insulation upgrade, windows and ACs replacement, and lights upgrade), and if further energy savings measures were applied, that would also increase the energy performance efficiency.

3.3.4 The energy retrofitting strategies

Existing retrofitting projects were geared towards either restructuring the building or enhancing the aesthetical appearance of the residential stock. Konstantinou [34] illustrated different types of refurbishment strategies that were used in the study as a base with an update for the Jeddah context. The used strategies (replace, add-in, wrap it, add on or cover it) were specified in that specific context which, in the KSA context, the cover-it strategy is disregarded from the study scope. To illustrate, the primary function of the "cover-it" measure is to add an additional external layer to the building, creating a double-skin system. According to a study by Hamza, this double-skin system can actually increase the cooling load in hot, arid climates, rendering it ineffective unless selective reflective glass is used on the outer side of the system [96]. Furthermore, building code restrictions on adding extra space to the exterior of a building pose a significant barrier to the adoption of the "cover-it" measure. However, the suitable strategy was categorised based on the used strategies (replace, add-in, add-on or cover-it) illustrated in Table 3.6.

TABLE 3.6 List of energy upgrade strategies.

Strategies	Replace	Add-in	Wrap-it	Add-On
Description	Replace Façade elements with better energy performance	Upgrade by adding from the inside of the building components (Wall, window, insulation)	Wrap the building with a second layer	Adding a Shading device or Structure element to the outdoor facade
Interventions	Replace entirely Replace partially (Walls, windows, connections, insulation)	Increase Wall thickness Internal insulation Cavity insulation Windows (panes, cavities, glazing) add sealant between components	External insulation (EIFS Exterior insulation), Second-skin façade	Adding (fixed, Active) shading devices or Adding balconies Merge balconies to indoor space if applicable
Benefits	New components with better performance Small disturbance to users	Appropriate for existing buildings Increase the thermal resistance. Individual decision making	Increase the thermal resistance using external insulation. No thermal bridging	Better energy performance on the developed parts Heat prevention increase Increased indoor space in some cases
Limitations	Significant impact on the building users' activities High initial costs	Thermal bridging needs attention. Decrease in livable space.	Not applicable for SBC limitations except for external insulation. High initial costs	Low WWR application limitations from the SBC

A The replace strategy

The replace strategy exchanges old building components (walls, windows, insulation, connections) with new ones separately, or it may also compose of altering the entire façade. The cost depends on the number of intervention activities used and the energy efficiency level of the materials used. Fewer interventions cost less while replacing an entire façade would significantly impact the buildings' energy efficiency with higher costs. However, the level of disturbance for the building users' activities needs to be considered early in this strategy application process to minimize the disturbance level. The disturbance might vary depending on the level of intervention. The greater the replacement intervention will result in more disturbances and vice versa.

B Add-in strategy

The add-in strategy is any upgrading activities of building components (walls, windows, insulation, connections) that take place inside the building that is appropriate for existing buildings. The add-in strategies give the option to keep the outdoor façade looking the same which is a great option for individual units of residential buildings. The critical issue of thermal bridging occurs with the connections between the building components, which need additional attention; in increasing the indoor wall thickness, the size of the liveable space decreases, which is essential to be considered in the solutions design process.

C Wrapping (wrap-it) strategy

The wrapping (wrap-it) strategy adds an extra layer to the building, like a second skin facade or full external insulation (EIFS). The Second skin façade would solve the thermal bridging issues. Still, if there are no restrictions on increasing the outdoor wall thickness from the SBC, the architect will modify the building aesthetically. Also, this option would minimise the disturbance level for the building users' activities compared to the replacement strategy of the entire façade but with higher costs. On the other hand, EIFS would have great potential for improving the thermal energy performance of the existing walls (no thermal bridges). The walls with stone finishing would need further investigation on the stone disassembly for its additional time and cost. However, the EIFS option has been used lately, but the costs were higher than the previous strategies.

D Add-On strategy

The add-on strategy is adding a shading device system or a structural element to the outside façade layer. The shading activity is only for improving the shaded parts of the building. The residential buildings' WWR is generally low due to the hot climate conditions. In the case of the merged balconies, increasing the indoor space would be appreciated from the building users' point of view when there are no merging restrictions from the SBC.

3.3.5 Energy performance challenges of residential buildings in Jeddah

In Jeddah, residential building envelopes have been designed with poor thermal properties. Several studies have assessed the thermal attributes (U-values) of existing residential building envelopes, including walls, windows, floors, and roofs. These studies found that the building envelope is a key element contributing to high energy consumption. Computational simulations for actual building cases were used in the studies [29], [30], [32]. From these computational simulations, several studies have shown where possible energy savings could be made [17], [29], [79]. Interestingly, one of the studies illustrated that with minimum interventions, a varied range of energy savings between around 15% to just below 50%, depending on the energy-saving intervention(s), could be achieved [78]. Life cost analysis is also employed to determine which saving intervention could save the most energy in the long run.

In the thesis, the primary challenge concerns buildings requiring energy upgrades due to poor thermal design. This poor design results in substantial outdoor heat gains from various building envelope components, affecting thermal comfort in indoor spaces Table 3.7. The thesis observes that the main contributors to high energy consumption are infiltration rates and thermal bridges. For illustration, in daily practice, the building users employ mechanical cooling systems, Air Conditioning units (ACs) to equalize the comfort temperature level in the indoor space. Therefore, some of the most pressing issues that need to be addressed to improve the energy performance of current residential buildings include a lack of information at various stages (from building codes to construction) as well as the presence of low energy tariffs. These factors highlight the deficiencies in the energy performance of building envelopes..

TABLE 3.7 Energy efficiency challenges, causes and results.

Energy Efficiency		
Challenges	**Causes**	**Result**
Poor thermal performance of envelope (wall, windows, no insulation)	Old SBC standards, inappropriate design, no insulations with high U value for walls	Outdoor heat gain, high energy demand, user discomfort
Low airtightness with a high infiltration rate	Inappropriate sealants or no sealants, poor components, materials	Outdoor heat gain, increased cooling load demand, high energy demand, user discomfort
Thermal bridges	No insulation, poor design	Outdoor heat gain

The following factors need to be looked at when upgrading the existing buildings to reduce the high heat gain from the outside of the building, reflecting the indoor thermal discomfort felt by the occupants:

- There is a lack of knowledge on the cost benefits of applying essential technical solutions for energy retrofitting of building envelopes. The defective thermal properties of the walls, roofs, and windows need to be addressed. Moreover, the old SBC code did not require a sufficient energy level, which was presented using low thermal resistance materials.

- There is a high rate of infiltration (low air tightness) in indoor spaces. These rates were not addressed in the previous building codes, and to date, there is still a lack of knowledge regarding the most efficient rate for existing residential buildings [97]

- There are thermal bridges that have resulted from poor thermal designs.

Even though all of the constraints have been correlated with each other, the previous discussion highlighted that the energy requirements in the old building code were the main driver of the current problem. The previous cheap energy costs and occupant behaviour also supported energy consumption in residential buildings. For instance, when the energy requirements and electricity tariffs were low, buildings were constructed with poor thermal properties, which required a higher cooling demand. The occupants responded to the thermal discomfort levels in the indoor space by using the ACs, which did not cost much money.

Lately, GCC countries have developed several policies towards lowering CO2 emission levels, which required several changes to be made by the respective governments as top and bottom approach decisions. The developments focused more on enhancing buildings' energy performance combined with activating the available renewable energy sources, raising the region's energy efficiency bar.

Recently, the Solar Decathlon Middle East (SDME) competition was geared towards the possibility of net-zero buildings in hot arid climate conditions. It considered the large area needed for PV solar panels to achieve a net-zero idea [98]. The results showed a primary need for efficient designs of the buildings combined with renewable energy sources. The Virginia Tech project mentioned an example of a remarkable annual kWh analysis that demonstrated the possibility of transferring a villa from an energy consumer to an energy producer, which raised the bar to reach a net-zero energy house [99].

The SDME competition was based on a different building typology than mid-high-rise buildings, namely villas, although the results could be beneficial as actual evidence of energy-efficient homes within a hot arid climate zone.

A recent local study by Aldossary[79] suggested an energy benchmark level for apartments in high-rise buildings in KSA ranging from 77- 98 kWh/m² per year, providing a lower carbon emission rate [79]. Also, Aldossary gave an example of an external wall thickness of 24 cm with 2.7 (W/m²k) U-Value, shown in Table 3.8. The author proposed an optimal solution for a 35 cm external wall thickness with a 0.257 U-Value. Another study by Alaidroos [29] extensively tested five energy efficiency measures [29]. The results expressed enormous energy savings that would significantly save energy cost subsidies, national oil consumption, and investments for new power plants. The suggested range of energy could be taken as a benchmark and reference level to be compared later with the results of the proposed scenario.

TABLE 3.8 Building elements specifications [79].

Building Element	Specification	Thickness (cm)	U-Value (W/m²k)
External wall	Mortar–red brick–mortar	24	2.7
Internal wall	Mortar–brick–mortar	24	3.38
Roof	Six layers (tiles, mortar, sand, insulation and reinforced concrete)	40	2.8
Floor	Seven layers (ceramic, mortar, sandstone, concrete, insulation, basement concrete and basement stone)	50	1.9
Windows	Single glazing	1	5.57
Doors	Wooden door	4	2.1

In addition, the study illustrates that the current energy consumption in KSA for apartments ranges between 114 -166 kWh/m² per year while 109-185.4 kWh/m² per year for Villas [30]. The results of the simulation-based studies illustrated actual upgrading possibilities of energy performance for the existing residential buildings, especially after regulating the upgraded SBC. The detailed study will be used as a reference level while further simulation validation is needed.

The SBC was upgraded in 2018, and the energy tariffs were increased. Then, in January 2021, the SBC national committee endorsed an upgraded building code for all new residential building construction built from July 1st 2021 and onwards. Interestingly, after the SBC endorsement, no\few construction permits were issued in Jeddah for at least three months until the committee lowered some of its requirements [73]. This study focuses on the existing residential buildings in Jeddah, categorised in Zone 1 according to the SBC classification, as shown in Table 3.9 [6]. The current SBC assigned upgraded U-Values to optimise the energy performance of the new residential buildings. Unfortunately, the existing residential buildings' performance levels are far below the upgraded SBC standards. The upgraded SBC energy standards (considered the best minimum requirements for zone 1) could be used as a minimum reference level for any energy upgrade solutions. Therefore, energy upgrade measures through retrofitting strategies (interventions) should be compliable with the current SBC U-Values.

TABLE 3.9 The minimum U-Values and R-Values for Air-Conditioned spaces and non-Air-conditioned spaces [6]. Note: F (W/m.K) and SHGC (Solar Heat Gain Coefficient) (0-1).

SBC required U-Values and R-Values for Zone 1	With ACs		With No ACs	
	U Value (W/m²K)	R-Value (m²K/W)	U Value (W/m²K)	R-Value (m²K/W)
Ceiling	0.202	5.0	0.4	2.5
Wall				
Wall above Ground	0.342	2.92	0.453	2.2
Wall Under Ground	6.473	2.92	6.473	None
Floor				
All	0.496	1.5	0.78	0.7
Steel beam	0.296	3.3	0.296	3.3
Other	0.188	5.3	0.288	3.3
Ground flooring	F-0.90	2.6 60cm	F-1.263	None
Doors	2.839		2.839	
Windows				
All connection	2.668	SHGC-0.25	3.695	None
Menwar (Shaft)	4.259	SHGC-0.35	10.22	SHGC-0.35

Interestingly, the upgraded SBC requires different U-Values for air-conditioned and non-air-conditioned spaces. Air-conditioned spaces require lower U-Values than non-air-conditioned spaces, which require higher U-Values. Perhaps, designing passive housing units would require higher U-Values if appropriately designed. The question is, who is responsible for checking whether the housing unit is designed passively or not? However, the building code could define the minimum R-Values or U-Values requirements by stating whether the space is air-conditioned or not. It also needs to consider the manipulation possibilities, especially when most of the buildings in Jeddah need AC systems.

Table 3.10 presents a comparison between GCC countries including KSA. The thermal requirements of walls, roof and windows (SHGC) are lower compared to other hot arid climate countries while the windows U-value is much higher than the others.

TABLE 3.10 Required Thermal Insulation Values in KSA, UAE, Bahrain and Kuwait.

Country	Required Thermal Insulation Values				Source
	Wall	Roof	Windows		
	U-Value	U-Value	U-Value	SHGC	
KSA (Zone1)	0.34	0.2	2.668	0.25	[6]
UAE (Dubai)	0.57	0.3	2.1	0.4	[100]
Bahrain	0.57	0.3	2.1	0.4	[101]
Kuwait	0.45	0.25	3.61	0.4	[102]

The cost is a crucial driver in the decision-making process in which saving measures need to be considered. The final solutions preferably incur minimal costs and efficient intervention solutions.

The study's primary focus articulates a framework of possible energy retrofitting intervention measures, considering the costs to provide high energy performance that meets at least the upgraded SBC energy standards for existing high-rise residential buildings in Jeddah.

3.3.6 Jeddah Climatic Challenges

Jeddah has the highest number of 6587 °C cooling degrees-days per year compared to other cities in KSA Table 3.11 [42].

TABLE 3.11 Cooling and heating degree-days for five cities in KSA.

City	Cooling Degree Days (CDD) (˚C-days)	Heating Degree Days (HDD) (˚C-days)
Jeddah	6587	0
Dhahran	5953	142
Riyadh	5688	291
Tabuk	4359	571
Abha	3132	486

The Jeddah climate is hot-dry with a maritime desert subzone [1]. Jeddah's maximum temperature is 48 °C, and the minimum is 13°C with different relative humidity ranges; Table 3.12 explains that in more detail in [30].

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TABLE 3.12 Temperatures and Humidity levels in KSA.

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
Max. Temperature	32	35	39	42	42	48	45	41.5	42	43	38	36.5
Min. Temperature	13	15.4	18	19	20	23.4	24.8	25	23.8	20	20	17
Relative Humidity	59	56	60	58	56	58	49	52	66	61	65	51

Alaidroos and Al-Hadhrami mentioned that residential buildings in Jeddah have an extremely high cooling consumption of 71% and the highest number of Cooling Degree Days [29], [39]. Also, Felimban noted that if a building does not have any thermal insulation, it will negatively impact the building users' energy behaviour [41]. Therefore, the outdoor hot air penetrates indoor spaces and heats the space, which requires mechanical cooling systems for more extended periods.

3.4 Overview of the existing residential building stock

3.4.1 Residential Building Stock in K.S.A.

The main goal of this section is to identify representative building typologies to use as a base to define design parameters for energy upgrades using envelope retrofitting strategies. The primary types of residential building stock in KSA (apartments, individual floors in traditional houses, individual floors in villas, standalone villas, and traditional houses) are enumerated by quantity within the administrative area, as shown in Table 3.13.

TABLE 3.13 Distribution of Types of Residential Buildings and Their Respective Quantities Across Various Regions in KSA.

Administrative Area	Type of Housing Unit					
	Apartment	A Floor in a Traditional House	A Floor in a Villa	Villa	Traditional House	Total
Al-Riyadh	284913	1607	130378	385600	47921	850419
Makkah Al-Mokarramah	**567697**	**10123**	**20659**	**114755**	**182934**	**896168**
Al-Madinah Al-Monawarah	148536	684	2475	36793	60113	248601
Al-Qaseem	14309	0	31402	95212	25642	166565
Eastern Region	247548	10570	30158	168307	57303	513886
Aseer	108986	1105	31614	108329	56982	307016
Tabouk	74382	273	1029	7465	37694	120843
Hail	13561	71	3383	31713	31057	79785
Northern Borders	9640	1863	3985	15791	6009	37288
Jazan	30257	299	11233	32710	102632	177131
Najran	26606	0	3530	16128	21858	68122
Al-Baha	26529	0	4927	22633	13603	67692
Al-Jouf	19690	213	2503	21027	14149	57582

The intention is to gather relevant information to correctly ascertain the current conditions of the residential buildings in terms of common building types, housing units' population, financial supporting program Sakani (my house), mid-rise building regulation changes, and ownership types.

In KSA, high-rise residential buildings account for approximately 50% of the building stock (commercial, governmental, agriculture, and industrial) [41]. The high-rise apartment units account for about 2.9 million units, around 53% of KSA residential buildings [32]. Moreover, Makkah province (where Jeddah is) has approximately 1 million units.

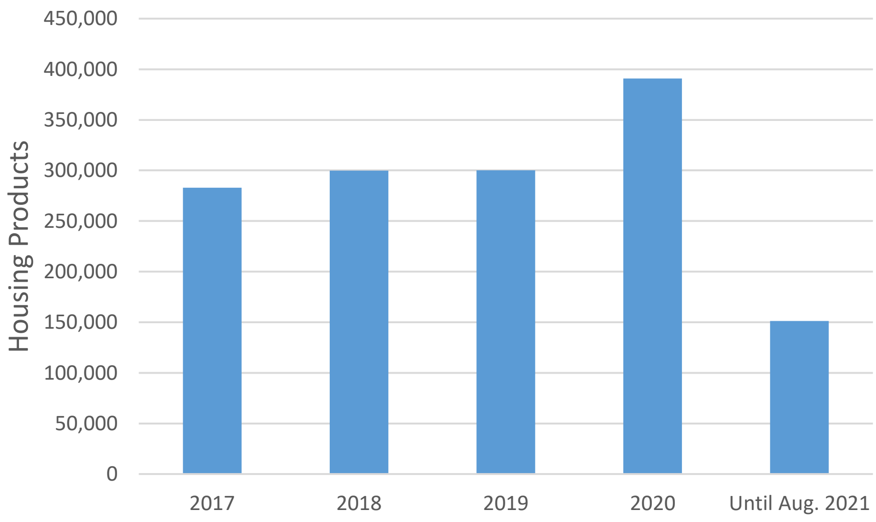

FIG. 3.6 Graph of Sakani Housing Products (1.4 Million) from 2017-2021.

In addition, the Sakani program's main strategic goal is to increase housing ownership from 47% to 70% by 2030. The program planned to offer different housing product solutions like providing a housing unit or financial support for the first housing unit.

Sakani was established in 2017 to accelerate the number of Saudi families that owned their own houses. 60% of the goal will be achieved by 2020. By August 2021, Sakani managed to accommodate more than 1.4 million households see Figure 3.6, which included various types of housing products (Residential free lands + loan, market units loan, self-construction loan, under construction unit loan, ready-made units loan, transferring the current mortgage to a subsidized loan, military member loan, civilians loan, education members loan). In order to meet the strategic goal, 40% more housing units are still in the delivery process [40].

Saudi citizens have preferred to buy apartments in mid-high-rise buildings due to the high availability of the apartments that have been offered since the Sakani program started (2017). The other reasons that have motivated citizens to choose apartments compared to the other housing products include affordability, location (close to the city centre), and short delivery time.

The apartment units were mainly mid-rise (3-5 floors), classified as residential. The mid-rise residential buildings in KSA were classified into two types; residential or residential + commercial, depending on the land use standards.

The residential mid-rise buildings had two changes in building code regulations, resulting in different building use and ownership categories (old, recent and new) see Figure 3.7. The first upgrade required the building owner to accommodate parking spaces on the first floor (ground floor) while offering the possibility of building a villa on the roof floor, which the thesis categorised as a recent type. In this scenario, the regulation change added multi ownership type to the building ownership, and it was observed in the past that potential homeowners would rarely accept to buy an apartment and be willing to share the ownership.

The regulation change offered additional yearly income for the owners if they built their villa on the roof and leased the rest of the building as apartments. Investors built many mid-rise residential buildings with villa roofs in this period. They sold them separately (apartments and a roof villa), which began the trend of multi-ownership of a single building.

Mid-rise building regulations have changed, and a villa roof has been banned, although parking is still required. In summary, the regulation changes affect the ownership types from single to multi-ownership, a change from 20 years ago when this was unacceptable.

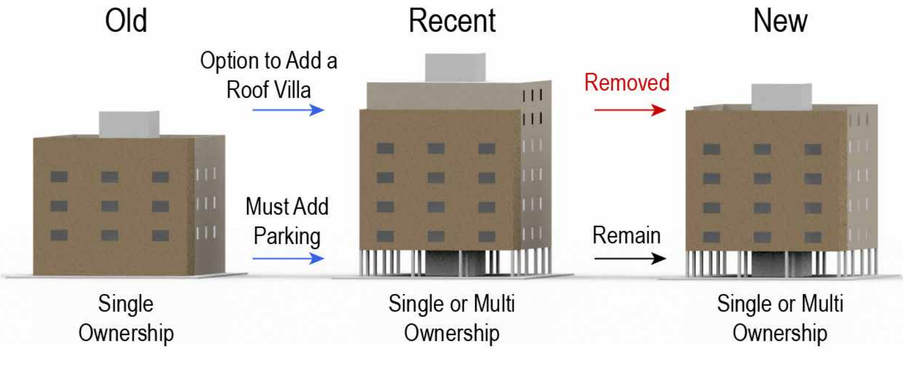

FIG. 3.7 The regulation changes affect the building ownership types.

The improvement of multi-ownership in building management is attributed to the enactment of updated building regulations and the establishment of the Mullak program in February 2020. This study concentrates on mid-rise residential buildings and investigates both types of ownership to suggest practical solutions. Figure 3.8 depict the diverse mid-rise residential building types found in Jeddah. Despite varying construction ages, the energy performance of these buildings remains comparable as they adopt a similar construction approach. However, discrepancies in ownership type may influence the proposed results, which will be elaborated on further in the subsequent text.

Old (3 floors) Old (4 floors) Old (5 floors) Recent (5 floors) New (5 floors) Recent (5 floors)

Old (3 floors) Old (4 floors) Old (5 floors) Recent (3 floors) Recent (5 floors) Recent (5 floors)

FIG. 3.8 Different types of mid-rise residential buildings illustrate the types of construction and ownership.

Several researchers have explored the Saudi residential building characteristics in varied aspects depending on the location and user profile. Aldossary identified several prototypes according to the official construction plans that were given to the researcher. Similarly, Alaidroos have described the construction methods and the HVAC specifications for a base case villa in KSA. However, this study has concentrated on the 3-5 floors residential buildings with multi and single ownership without a villa roof due to the latest SBC upgrade regulations. Also, the multi-ownership buildings would be the main focus in order to reach more housing units. Furthermore, the proposed scenarios have also considered single ownership. Categorization of the focused residential buildings has concentrated on the construction method and the materials used, and it has not been based on the built history.

3.4.2 Common Construction Method

Usually, the most used materials for building construction in residential buildings were reinforced concrete from readily available, durable and affordable materials. Skeleton structure (frame structure) systems were most commonly used in residential construction as a primary construction method [103]. In general, the construction phases of a mid-rise residential building follow typical construction steps, as shown in Figure 3.9.

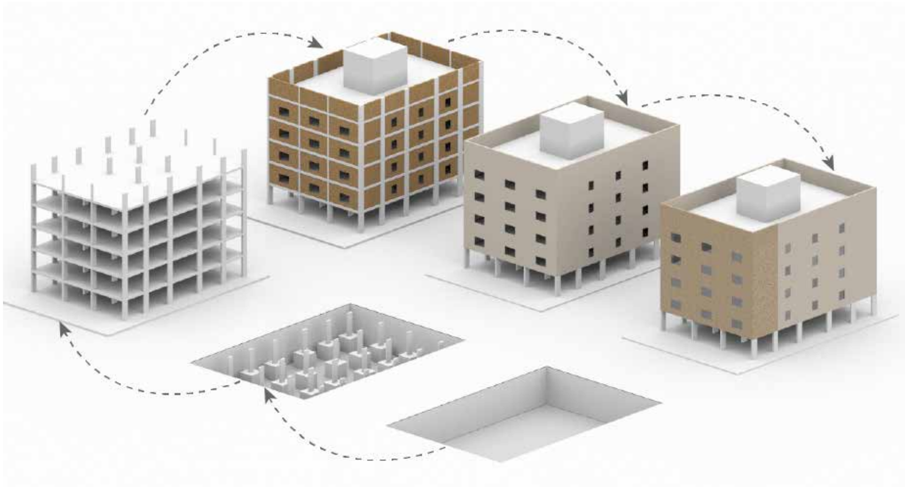

FIG. 3.9 Typical construction method.

The residential mid-rise construction phase starts with the underground phase, the drilling step, and the column foundation. After that, the concrete Skeleton Structure Phase is the most commonly used system for mid-rise buildings and other building types in KSA [103]. The reinforced concrete material is used for its affordability, availability and durability. The construction of the skeleton structure must follow specific procedures from the foundation to the roof slab step.

Next is the Block Walls (Wall-Filling) phase, which uses blocks to fill between the skeleton columns; see the red walls in Figure 3.10. The material that can be used varies; it depends mainly on the assigned budget, a low (cheap) budget, especially for investors. The common use materials for wall fillings are Cement block, red block, Burkani block or very rare Siporex block. Every type of wall-filling has different properties and different thermal conductivity levels. Typically, the wall construction is built as 20 centimetres blocks for wall-filling, illustrated in Figures 3.10 and 3.11.

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The third phase is cement finishing (Mortar) which is the first layer of finishing that comprises adding mortar (2 cm cement) to both sides of the blocks, as shown in Figure 3.10. The final phase finishes the whole envelope with paint or stone. How it was painted or decorated depends on the building owner's budget, some owners have more budget and can add different kinds of stone for the front Façade for aesthetical purposes, as shown in Figures 3.10 and 3.11.

FIG. 3.10 20 centimetres blocks for wall-filling within the skeleton structure.

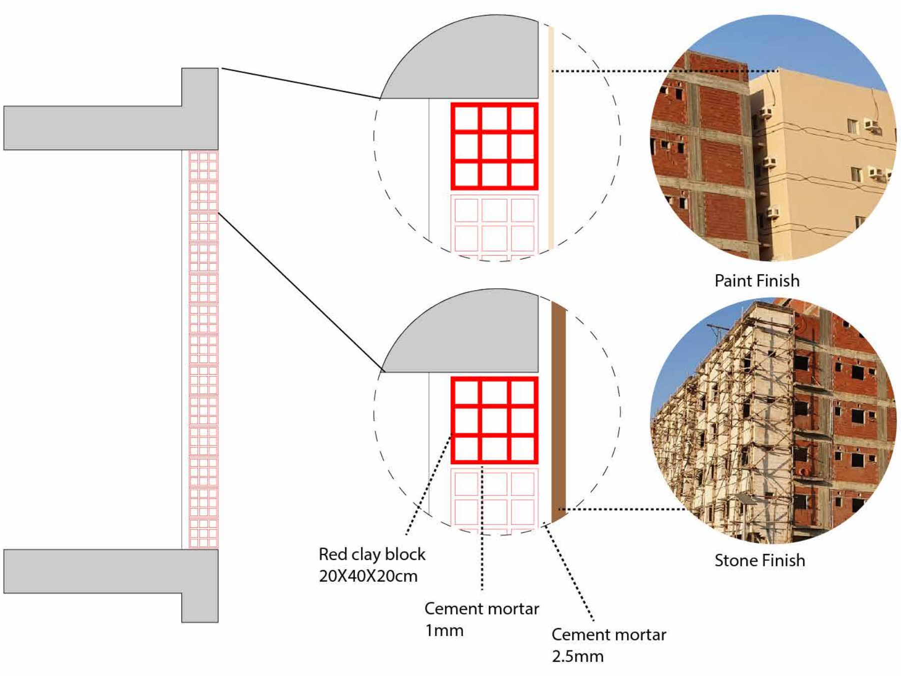

FIG. 3.11 Typical Wall section demonstrating materials used in construction.

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The typical materials used in the construction will illustrate the building envelope materials to define and clarify the available materials for each targeted envelope component within the Jeddah context [103]. The materials of constructed residential buildings could be used later as a starting point for energy-upgrading applications such as replacing or upgrading solutions (walls, insulation, windows (frames, glazing and pans) and sealants) to support the design possibilities. Also, the section will discuss the related materials with existing residential buildings where materials were responsible for outdoor heat gain. As discussed earlier, the construction method has four stages: skeleton structure, wall-filling, cement mortar, and finishing. The typical material for the skeleton structure is reinforced concrete for its availability, durability and affordability[103]. Various materials have been used for the different stages of building construction. The following sub-section, Figure 3.11, explains the material variations for wall fillings (blocks), insulations, finishing, windows and sealants.

A Wall fillings (blocks)

Felimban expressed that 70% of residential buildings in Jeddah were not insulated [7], [41]. In general, a typical residential building wall is comprised of single bricks (red blocks, cement blocks, Burkani blocks or Siporex (autoclaved aerated concrete)) covered with mortar finishing (2 cm cement layer) on both sides.

Walls with openings contain a window frame with a single glazed pane which will be elaborated upon in a later sub-section. The current wall thermal energy levels present a great opportunity to upgrade their energy performance. Any energy upgrade scenarios ought to build up upon the used types of blocks of Jeddah's residential buildings. The wall upgrade intervention could be a combination of increased thickness by adding a wall, insulation layer and air gap to the indoor space. All scenarios will tighten the indoor space while thermal bridges still exist from connections which is another challenge that needs to be considered. The commonly used wall materials have been illustrated in Figure 3.12, which presents the four most used block materials (cement block with holes, red block, Burkani block and Siporex). In 2021, the blocks factories were required to meet specific thermal properties to meet the upgraded SBC see Table 3.14.

TABLE 3.14 Wall materials U-Values and R-Values [104].

Wall Materials (20 cm)	K-Value W/mK	R-Value m²K/W	U-Value W/m²K
Cement Block with wholes (no filings)	0.976	0.204918	4.880
Red Block with wholes (no filings)	0.382	0.52356	1.910
Burkani Block (no filings)	0.36	0.555556	1.800
Autoclaved aerated concrete (Siporex)	0.156	1.282051	0.780

Cement Block

Burkani Block

Siporex

Red Block

FIG. 3.12 Various types of building blocks [105].

B The insulation materials

The thermal insulation purpose in hot climate regions is to reduce the heat energy transport through the component. An indoor or outdoor layer is applied to the walls and the roof surfaces. Also, it is categorized, depending on its material origin, as conventional (organic or inorganic commercially available products) and sustainable (natural, recycled) [106]. As mentioned earlier in this study, most KSA residential buildings are not insulated, which is a significant factor to be tackled to improve energy efficiency by minimizing or preventing outdoor heat transfer to indoor spaces. KSA's most commonly used and available insulation materials are polystyrene, polyurethane foam, mineral wool, glass wool, Perlite and Siporex, as shown in Figure 3.13 [104], [106]. Different properties must be determined in the design process to select a suitable insulation material, such as availability, cost, installation difficulty, soundproofing, and fire resistance.


Polystyrene Polyurethane foam Mineral wool

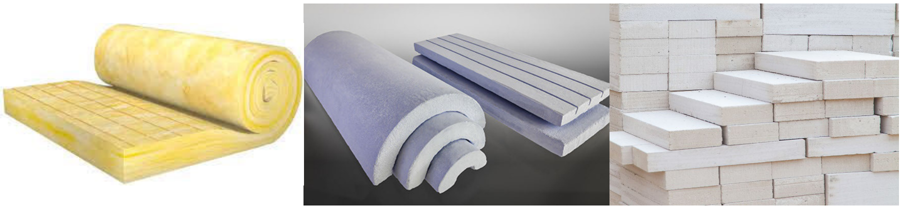
Glass wool Perlite Siporex

FIG. 3.13 Various types of insulation materials [104].

C Finishing

The common finishing layers are mortar (2-2.5 cm cement layer on both sides of the wall) with a painting or stone layer on the main façade for aesthetical purposes. The mortar finish has a thermal conductivity of 0.72 W/m.K. while painting and stone are varied based on the material selection. In the KSA context, in most cases, the stone layer is used for aesthetical purposes, while it would be more beneficial if used to improve thermal performance. In addition, some painting companies offered thermal resistance, which has been newly introduced to the market at a higher price than other comparative materials. The finishing layer options need to be considered in energy upgrade scenarios, especially when the façade has a stone finishing, which requires a stone disassembly plan (cost and time).

D Windows

The windows upgrade measures have a significant role in energy efficiency even when windows account for a maximum of 25% of the total façade area [107]. However, the window (frames, glazing and pans) significantly impacts the outdoor heat transfer to the indoor space through the gaps between the frames and the wall and within the window frame. Also, the Solar Heat Gain Coefficient (SHGC) through the window panes should be considered. Usually, aluminum frames were used for their durability and availability in the market. In recent years, the use of unplasticized Polyvinyl Chloride (uPVC) has increased due to competitive prices and availability. In addition, uPVC has shown higher thermal resistance than other available materials, such as aluminum or steel. As timber and steel were rarely used in window frames due to their high cost and availability, they have been excluded from the study scope.

There are different types of window glazing and pans with different U-Values and SHGC, as Table 3.15 illustrates. The main factors of thermal resistance levels for any window glazing are the number of pans, the colour and the size of the cavity between the pans.

TABLE 3.15 Window glazing types and heat transfer level [29].

Glazing type	U-value (W/m2.K)	SHGC
SBC requirement for glazing	2.66	0.25
Single clear	6.31	0.86
Double clear air	3.23	0.76
Double clear argon	2.61	0.76
Double LoE clear air	2.47	0.6
Double LoE clear argon	1.48	0.59
Double LoE TINT air	2.43	0.39
Double LoE TINT argon	1.46	0.37
Double LoE sel clear air	2.32	0.42
Double LoE sel clear argon	1.3	0.42
Double LoE sel TINT air	2.32	0.3
Double LoE sel TINT argon	1.3	0.28

E Sealants

Sealant material is a filling material between the wall (blocks) and the window frames, which is used to prevent air and water penetration into the indoor space [34]. In the KSA, the sealants measure is another significant factor preventing indoor space from the outdoor heat. The lower the quality of sealants, the more heat is transferred to the indoor areas, resulting in more mechanical cooling demand. Sealant compositions are categorized into silicone sealants, hybrid polyurethanes sealants and polyurethane sealants.

3.5 Design Parameters and KPIs

The design parameters define the study scope borders and the Key Performance Indicators (KPI) for tracking the suggested cost, energy and users' comfort scenarios.

The parameters have been demonstrated based on three categories: climate, users, and the type of building. Initially, the climatic conditions of the case study (Jeddah) showed the yearly need for cooling degree days is 6587 °C-days, which determines how many degrees for cooling are needed either by natural cooling or mechanical cooling systems. The hot-arid climate in Jeddah rarely has rainy days, and the humidity level is relatively high, as illustrated in Table 3.11. The main challenge is achieving (19-22 °C) users' thermal comfort level for indoor space while outdoor temperature ranges between (32-48 °C). Also, the building envelope components have to meet the current SBC energy standards as a minimum in terms of U-Values and infiltration rates.

The primary building KPI is the energy consumption per square meter (kWh/m^2) per year which will be used as the primary indicator of improvement evaluation. Further, different indicators have to be considered, such as U-Values (W/m^2K) for façade components, including windows frames, SHGC for windows panes, and the infiltration rate as air change per hour AC/H in order to evaluate the energy efficiency of each component. In addition, cost analysis is essential to assess and compare the proposed scenarios with the current scenario. Also, indoor space size indicates how the upgrading scenario would tighten the indoor space in terms of 3-dimensional space, which depends on the proposed scenario. The operational life cycle and initial costs are the main KPIs for a cost analysis to be compared later with current buildings for different payback times.

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3.6 Possible Energy retrofitting upgrading scenarios

As shown in Table 3.6, earlier illustrates the possible energy retrofitting strategies (replace, add-in, add on or cover it) and their intervention activities. The energy upgrading scenarios could combine intervention activities from different strategies. The aim is to upgrade the unit's energy performance to meet or improve the SBC energy standards. Upgrading focuses on indoor and outdoor interventions depending on the components needed. The selection of retrofitting interventions is according to the ownership type (single and multi), which starts from the indoor to the outdoor interventions.

For the multi-ownership type of building, the replace strategy is recommended for windows and sealants. Also, the add-in strategy could be used for adding a wall and insulation from the inside. In addition, add-ons can be used to add shading devices from the outside. Single-ownership buildings could use the same strategies as multi-ownership buildings with an additional option: cover-it (wrapping it) on the outside, such as EIFS.

The study is divided into four parts; the first part is walls that demonstrate the promising possibilities based on the used materials of the case study: Cement Block, Burkani, Red clay block, and autoclaved blocks (Siporex). The existing essential wall parts U-values are illustrated in chapter 3 for the four block types. The simulation validation chapter (chapter 4) has focused on the cement block material scenario as it shows the lowest energy performance and other materials would have the same impact. The concept is adding different layers, either indoor or outdoor, to the existing wall in order to reach the SBC standards. The replacing strategy could be an option if the building owner is single. However, the layers are the insulation comprised of block layers finished with cement mortar.

Additionally, the "cover-it" strategy involves external interventions such as EIFS, which can enhance the thermal resistance and air-tightness of a building while minimizing thermal bridging without compromising indoor space [34], [108], [109]. At the same time, the initial costs are higher than indoor interventions. However, energy retrofitting scenarios need to commence with possible indoor interventions. Then, outdoor interventions could be applied depending on the case situation.

The thesis noted three possible types of walls have existed in the mid-rise residential buildings in Jeddah: a wall, a wall with openings, and two walls as a balcony (very limited). Essentially, the concept is to convert the balcony to either make a single wall that adds the balcony space to the indoor space or left as it is, enhancing the indoor wall and using the balcony space and the outdoor wall as a shading option. As mentioned earlier, the key performance indicator is the U-Value level, which is 0.343 (W/m²K). The wall thickness is calculated after each intervention to indicate how much the indoor space has decreased.

In the tables in the index, all basic existing wall types did not meet the SBC U-Values level and were highlighted in red. Interventions A (1, 2, 3, 4 and 5) and B (1, 2, 3, 4 and 5) have been evaluated for their total U-Value. If the total U-value of the intervention was highlighted in red, then an additional intervention was needed until the total U-Value met the SBC energy standard, highlighted in green.

The typical double wall with an insulation layer in between is well-known as a best practice as recommended by SEEC [107]. However, there are minimum requirements to meet the SBC U-Values, Table 3.9 illustrates the minimum level of U-values and the expected wall thickness of each scenario.

The second part is windows, where energy upgrade interventions deal with window frames and the number and type of glazing pane(s). Typically, the windows frames use aluminium material which has a low thermal conductivity of 175 W/m.K compared to uPVC 0.13 W/m.K and timber 0.12 W/m.K. The SBC required 2.66 W/m2.K U-value for window frames, which needs retrofitting scenarios to upgrade the window frames with uPVC or timber; often, timber is not affordable in KSA.

Window glazing (Pane(s)) needs to meet at least 2.66 W/m^2.K. As shown in the index, the glazing U-values are highlighted in green when meeting the required level from SBC of glazing types. Also, the SHGC is high in all provided types, and every type needs an additional energy upgrade measure, such as thermal films or adding shading device systems. The concept is to use a replace strategy to change the entire window.

The third part is sealants which is a minor upgrade but essential for the infiltration rate levels. This part would illustrate the importance of the infiltration rate by showing the sealant materials appropriate for the Jeddah context. Moreover, sealant materials seal the connection gaps between the building parts (for example, between a window and a wall) to prevent uncontrolled air and water leakage [110]. The sealants come in different application forms, such as membranes, expanded foam, gun-applied tapes, and fillers; the type of sealant chosen depends on the leakage type (water or air).

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The most used sealant material for air barriers is a silicon-based type. The air leakages often occur around the window frames (a connection gap) and within the frame parts [97]. The different sealant materials have an appropriate thermal resistance level depending on the quality and whether they are appropriately installed [111]. The concept is to replace or add sealant materials to air-tighten indoor spaces.

The fourth part is the roof on the top housing units, which have more energy demands than those below. The roof thermal resistance needs to be considered in any energy upgrade for top housing units since the roof units have more heat gain exposure than those below. Typically, the roof is flat and constructed with four or five layers, as mentioned earlier. The current roof U-value for the Jeddah context is 2.8 W/m^2.K with 0.4-meter thickness [30], which will be validated later in the simulation chapter. The SBC regulations currently require 0.202 W/m^2.K U-value for roofs which could be reached in different ways. The fundamental way is to add an insulation layer with appropriate level of heat resistance to meet the SBC U-value requirements.

Additionally, the study noted that the current mid-rise residential building stock has two types of ownership, single or multi-ownership (housing unit scale). Proposed interventions must provide energy enhancement possibilities for multi- and single-housing unit owners. For multi-ownership buildings, an add-in strategy can be employed to enhance the U-value of walls, including replacing windows and sealants. In contrast, for single-ownership buildings, the same strategy can be employed along with the possibility of employing an additional cover-it-up strategy using EIFS.

Moreover, housing units on the top floor should consider interventions to upgrade the energy efficiency of the roof, as will be detailed in subsequent chapters. Also, the forthcoming chapter aims to validate the suitable scenarios, including investigating the required infiltration rate that needs to be considered. However, insufficient research has been conducted on the current rate in residential buildings in the KSA as no/few research on monitoring the current energy performance of housing units.

However, the energy upgrading scenarios centred on enhancing the thermal heat resistance for the current envelope in mid-rise residential. Accordingly, the tables in the index will furnish preliminary guidance for the subsequent chapter to authenticate the most suitable scenarios.

3.7 Conclusions

This chapter discussed the possible energy retrofitting strategies and available materials within the Jeddah context, suggesting a framework for selecting the most promising scenarios of energy retrofitting interventions for mid-rise residential buildings. The framework has discussed the potential of energy retrofitting strategies within the Jeddah context.

The state of the art has illustrated the available energy upgrading strategies based on the possible interventions. Many studies have shown promising energy savings ranging from an increase of 15%-72% depending on the employed conservation measures. Lately, energy costs have increased by more than triple, raising attention to the defective energy performance levels of the existing residential buildings. The harsh hot climate has forced energy efficiency development, which helped to upgrade the KSA building code to higher standards. The energy efficiency benchmark levels have shown promising energy upgrade possibilities for existing buildings.

Different variables were briefly discussed in the context section to define the conceptual boundaries for energy upgrades. Six variables were defined and reviewed: residential buildings stock, typical construction method, current energy performance, the material used for existing mid-rise residential buildings, design parameters and KPIs. The study has outlined the available materials and reviewed the strategies used in the energy retrofitting solutions: wall, window (frames, window pans, sealants) and roof. Also, the building case study characteristics were reviewed to limit the scope within the residential building sector. The mid-rise buildings category in Jeddah city was the main focus of this study. All variables were reformed since recent development occurred in 2018, which have been briefly addressed within this study.

The study has also discussed the potential energy retrofitting strategies in the Jeddah context using four different retrofitting strategies (replace, add-in, wrap-it and add-on); the available measures for each strategy have been defined and presented.

The energy upgrading intervention possibilities have targeted the current SBC energy standards. The proposed interventions that were provided depended on the building envelope component that needs specific energy upgrades. In the next chapter, the simulation process is necessary in order to validate the possible promising scenarios. The possibility to mix, match and pick between energy retrofitting interventions is able to create different scenarios that need cost analysis to decide which scenario is appropriate and best.

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To summarize, the presented framework for designing possible energy upgrade interventions is appropriate for the Jeddah context. However, more detailed information is needed to determine the most promising solutions.

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4 Energy Retrofitting Scenario Validation for Possible Energy Savings

Chapter 2 defined various energy upgrading scenario possibilities that need further validation. Therefore, this chapter validates promising scenarios using a digital simulation tool (DesignBuilder). The DesignBuilder tool is used to determine the energy savings for selected retrofitting scenarios.

First, Section 4.1 introduces the need for energy savings validations. The methodology in Section 4.2 illustrates the validation tool and the processing required to reach the results. Then, Section 4.3 presents the design parameters and the benchmark. This section illustrates a recent benchmark for new construction buildings and the average annual energy consumption according to previous research. Next, Section 4.4 demonstrates a case study of a typical residential building in Jeddah, including different parameters (floor plans, building fabric, user profile, and building ownership). Section 4.5 provides a detailed description of the selected ER scenarios. Subsequently, Section 4.6 presents and analyzes the results, and Section 4.7 discusses the analysis outcomes. Finally, Section 4.8 presents the conclusions of possible energy-saving options with different ranges of savings percentages.

4.1 Introduction

In the Kingdom of Saudi Arabia (KSA), building energy consumption is a major contributor to oil consumption and a significant expense for building owners and occupants [41]. Existing building retrofitting is a key strategy for reducing energy consumption [33]. However, retrofitting existing buildings can be difficult due to the design, climate, and occupants' behavior [20]. The government has introduced numerous initiatives to promote energy efficiency and renewable energy, recognizing the significance of energy efficiency in buildings [112]. However, the retrofitting of existing buildings has been slow due to a lack of awareness, funding, and technical expertise [20].

This chapter presents a case study of a residential building in Jeddah, Saudi Arabia, as well as proposals for several retrofitting strategies to improve the building's energy performance. The building is a typical residential mid-rise structure comprising eight apartments. Using key performance indicators such as the average annual energy consumption (AAEC), the energy efficiency of the building is compared before and after the retrofit. The proposed retrofitting scenarios consider improvements to the building envelope and HVAC systems. Additionally, the impact of occupant behavior on energy consumption is considered.

The results indicate that a scenario involving extensive energy retrofits can significantly reduce the AAEC. The study examines the challenges and opportunities associated with retrofitting existing buildings in Jeddah city. The chapter emphasizes the significance of a holistic approach that considers numerous factors when retrofitting existing buildings. The potential for energy savings as a result of retrofitting existing buildings is also examined.

In addition, the chapter discusses uncertainties and their effects on the AAEC, including the infiltration rate (ACH50) and the user thermal comfort temperature. In the simulation of energy from the basic model, an infiltration rate of 20 ACH50 was used, and attempts were made to generate scenarios targeting a rate of 4 ACH50, as required by SBC standards. Outdoor scenarios could only be applied to the entire building and not to individual apartment upgrades. The simulation results show a significant reduction in annual average energy consumption (AAEC) when a scenario involving a deep energy retrofit was utilized.

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The conclusion of the chapter discusses the implications of the study for policy and practice, including the need for incentives and regulations to encourage the retrofitting of existing buildings with energy-efficient components. The study contributes significantly to the literature on the energy retrofitting of existing buildings in Jeddah and can inform policy and practice in similar contexts.

4.2 Methodology

A mixed-methods approach, encompassing qualitative and quantitative techniques, was employed in this chapter to provide comprehensive results contributing to the existing literature on energy retrofitting of existing buildings in Jeddah. Qualitative data were collected from the relevant literature and related studies from previous chapter, forming a solid foundation for exploring the energy-saving potential of retrofitting measures using the Design Builder (Version 7) digital software (Energy Plus).

To examine the energy-saving potential and improve the energy efficiency of existing apartments in Jeddah, energy retrofitting scenarios were analyzed for eight apartments within the same building. A simulation tool was used to assess the current energy consumption (energy demand) and determine the potential energy savings for each scenario, normalized per net floor area.

The objective of this chapter was to evaluate and compare the energy-saving possibilities across different energy retrofitting scenarios, utilizing simulation software. To establish the simulation parameters, several steps were undertaken. First, a section of essential design parameters and energy benchmark levels were extracted from the previous chapter, which play a crucial role in highlighting specific variables. Second, the case study was described, as it was necessary for digital modeling. Data were collected from various sources, including floor plans, apartment orientation, component materials and U-values, user activities, and mechanical AC systems. Third, specific uncertainties that affect energy savings results, such as the infiltration rate and user thermal comfort (setback air temperature), were identified. Fourth, an overview of the energy upgrade scenarios and interventions was formulated. Finally, the simulation results were analyzed to evaluate and compare the energy savings achieved by each energy upgrade scenario. Additionally, the study normalized the energy consumption by using the net floor area. Further illustrations will follow in the next sections, and Figure 4.1 shows the structure of Chapter 4 to help readers understand the chronological steps of this chapter.

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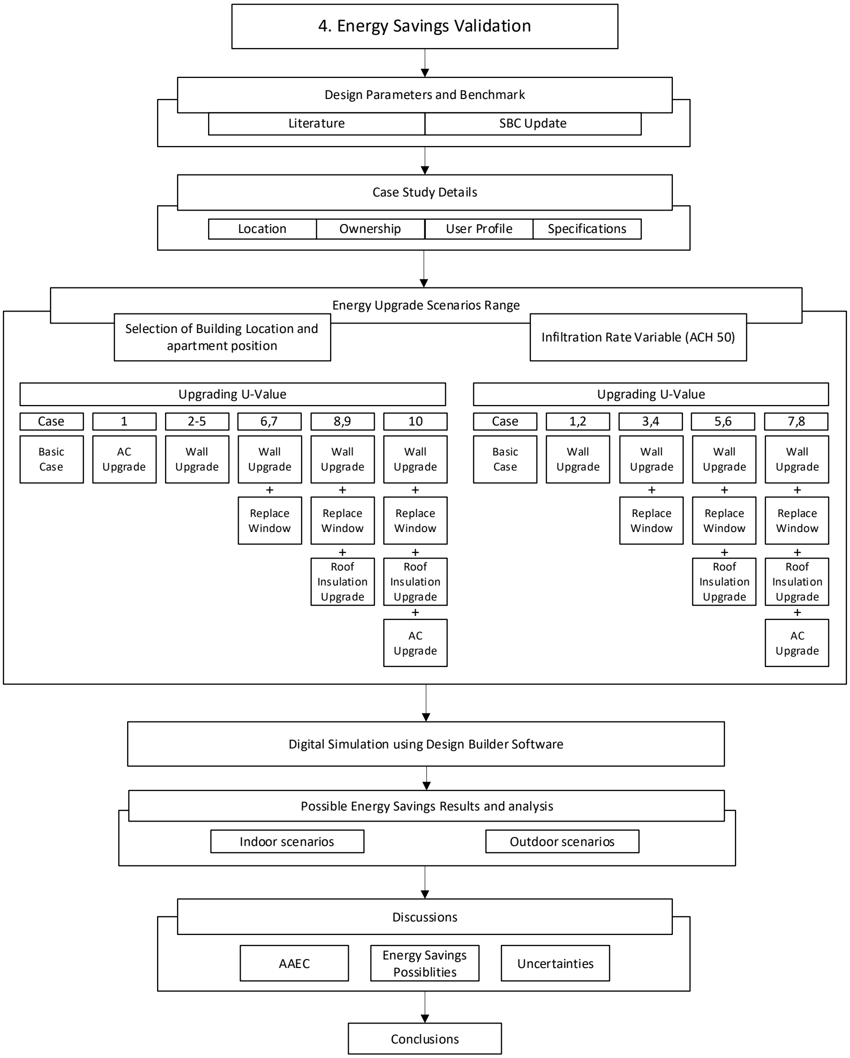

FIG. 4.1 Research structure of Chapter 4.

4.3 Design Parameters and Energy Benchmark

This section defines the design parameters and the energy consumption benchmark levels to limit the study scope and to enable energy upgrade scenarios.

Key performance indicators (KPIs) are essential for scenario evaluation. The main KPI is the AAEC (kWh/m²/ year), which was used as a KPI to evaluate the various upgrade scenarios compared to the original case. The evaluation of each apartment was based on at least one of the following: u-values (W/m²K), thickness (cm), infiltration rate ACH50, SHGC and WWR (for windows), and Cop (for AC units).

The hot-arid humid climate conditions in Jeddah require mechanical systems in all indoor spaces, which was also concluded by other researchers such as Felimban and Alaidroos [29], [41]. In addition, it is essential to consider the building location within the neighborhood, as this could also affect the AAEC for each apartment in the building.

The selection of building types was based on the number of housing units and the new buildings that the KSA Ministry of Housing developed. Apartments account for more than 50% of the total housing units in the KSA [51].

The construction method, which is based on a concrete skeleton structure (CSS), was the main focus of this research, as most buildings in Jeddah have a CSS; the history of the buildings was not taken into account. Furthermore, the construction steps of a CSS comprise walls that are infilled with blocks, plaster/cement finishing, and aesthetical finishing. The SEEC and Felimban suggest that more than 70% of the residential buildings in Jeddah were not thermally insulated, emphasizing the necessity for energy retrofit upgrades of the existing building envelopes [2], [41].

The Saudi Building Code (SBC) has upgraded energy efficiency requirements in energy benchmarks. In February 2022, the SBC National Committee lowered the energy efficiency requirements due to comments from construction companies in practice and the reluctance to issue new construction permits for residential buildings. Table 4.1 illustrates the specific value changes in respect of energy requirements from different upgrades of the SBC by the National Committee.

TABLE 4.1 SBC energy requirements upgrades (Red numbers indicate the changes) [6], [107], [113], [114].

	Wall Constr. (U-value) W/m²K	Roof Constr. (U-value) W/m²K	Ground Floor Constr. (U-value) W/m²K	Repeated Floor Constr. (U-value) W/m²K	Window Glazing	Rate		
						(WWR) Max	Air Infiltration (ACH 50)	HVAC System Efficiency COP
Started to be applied by 01/07/2021	0.342	0.202	0.49	0.49	(u-value) 2.66 SHGC =0.25	25%	4	4
Updated on 23/08/2021	0.403	0.272	0.49	0.49	(u-value) 2.66 SHGC =0.25	25%	4	4
Updated 21/02/2022; ends by the end of 2023	0.611	0.272	0.49	0.49	(u-value) 2.66 SHGC =0.25	25%	4	4

In Aldossary's research, an AAEC was established for different residential buildings in the KSA, although the study only covered the first two floors of mid-rise residential building types [30].

Unfortunately, the top floors of buildings have been found to require more profound energy upgrade interventions in order to perform better, as they are more exposed to the sun's heat and radiation due to additional external surfaces. In addition, researchers have observed a range between 116 and 165 kWh/m²/year in respect of the AAEC, which is predicted to be far more for top floors. However, Aldossary proposed AAEC values in the range 77-98 kWh/m² to reach a low carbon energy consumption level [79].

Several researchers, including Aldossary, Alaidroos, Krarti, and Hijazi, have explored different sets of energy retrofit measures that could reduce the energy consumption for the residential building sector by 37%, 41.5%, 50%, and up to 80% when applying a hybrid system (passive and two active cooling systems) [29]–[31], [38]. In the literature, the prediction of energy savings for existing buildings has been highly optimistic when applying different energy-saving measures. In this study, detailed energy retrofit scenarios have been defined in order to achieve a more realistic estimation of energy-saving possibilities for specific units in Jeddah city. Other factors, such as the infiltration rate (ACH50) and user thermal comfort temperature (C°), have also been included in this research, impacting the AAEC results.

4.4 Case Study Descriptions

4.4.1 Building Location and Position Selection

The selected case study was the residential building described in detail in Section 3.4. Jeddah’s climate and location have been described in considerable detail in Section 3.3.6 and by Felimban, Talep, and Aldossary [30], [41], [115]. The building position that was eventually selected was based on simulation testing of six positions of a typical building in an urban setting. Then, the worst case was selected, where the average energy consumption was the highest. This will be further shown in the simulation progress section.

4.4.2 Building and Apartment Descriptions

Generally, the land area for a residential building varies between 20m×20m, 20m×30m, 25m×30m, and 30m×30m, with a built-up ratio of 60% [6], [116]. The building case was extracted from actual plans of a mid-rise residential building provided by an architectural firm [117]. However, the case is based on a land size of 750m² (25m×30m), resulting in a built-up floor area of around 450 m². The selected building contains eight apartments (two per floor), and the first floor (ground floor) has parking spaces and other services such as driver rooms and the main entrance. The apartments mainly face either west or east. However, the east and north sides face the neighboring buildings, while the west and south sides face the street. These factors have an effect on the AAEC for each apartment. Each apartment has three bedrooms, a living room, a kitchen, a dining room, a reception room, a maid room, and three bathrooms, as shown by the floor plans in Figures 4.2, 4.3, and 4.4.

FIG. 4.2 First floor plan (ground floor) (14 Parking spots, 6 Driver rooms, and 1 guest room).

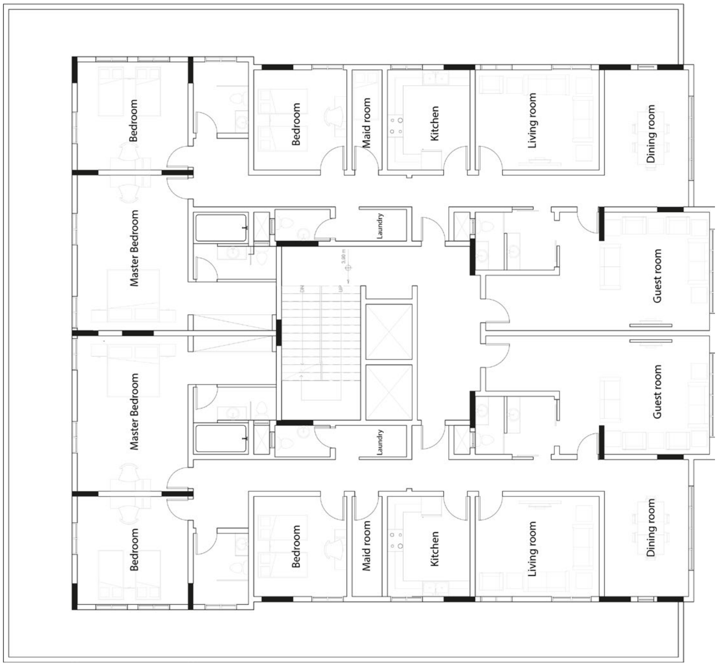

FIG. 4.3 Repeated floor plan .

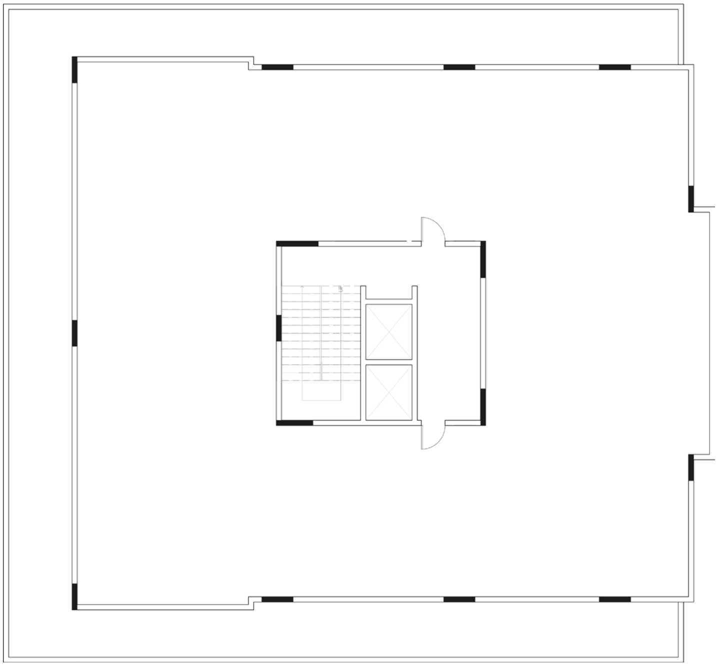

FIG. 4.4 Roof floor plan.

The building fabric was defined and illustrated based on previous studies and material properties. Tables 4.2, and 4.3 demonstrate every component in respect of total U-values, component thickness, and other variables. Additionally, the selected case study features a 10% Window-to-Wall Ratio (WWR). In scenarios where the WWR exceeds 10%, window upgrade measures would result in greater energy consumption savings. The apartments on the east side of the building have the same floor area, which is around 215 m², while on the west side the area is around 225 m².

TABLE 4.2 Building specification.

	Number of Floors	Total Number of Apartments	Area of Apartments	Building Location	Total Number of Occupants in the Building	Cooling Set Point	Cooling Set Back
Description	4 floors + parking floor (parents (2)+ kids (4)+ a housemaid)	8 apartments (2 per floor)	West 215m² East 225m²	Jeddah (South East)	56 occupants (parents (2)+ kids (4)+ a housemaid)	24 C°	26 C°

TABLE 4.3 Building fabric description and current energy values of building components.

Building Component	Detail Description	Thickness (mm)	U-value (W/m²K)
Wall Construction	20 mm cement/plaster/mortar inside +200 mm concrete block heavy weight +20 mm cement/plaster/mortar outside	240	2.676
Roof Construction	20 mm ceramic/porcelain top side + 20 mm mortar + 80 mm sandstone, 1.83 W/mk + 5 mm asphalt1 + 200 mm concrete, reinforced with 1% steel + 20 mm plaster bottom	345	2.81
Ground Floor Construction	25 mm ceramic/porcelain top side + 25 mm mortar + 80 mm sandstone, 1.83 W/mk+ 100 mm concrete, reinforced with 1% steel + 5 mm asphalt1 + 50 mm cast concrete + 150 mm stone basalt + 2 mm soil-earth	437	2.269
Repeated Floor Construction	25 mm ceramic/porcelain top side + 25 mm mortar + 80 mm sandstone, 1.83 W/mk + 200 mm concrete, reinforced with 1% steel + 20 mm plaster bottom	350	2.403
Window Glazing	Single-clear (SHGC=0.86)	3	5.894
Window Frame	Aluminum frames	5	5.881
	Details	**Rate**	
(WWR)	The percentage of the total window area to total wall area	10%	
Air Infiltration Rate (ACH 50)	The assumed rate is based on the blower door test (BDT) rate, which assumes that the indoor area is pressurized under 50 PA	20	
HVAC System efficiency	AC window type	1.8 COP	

4.4.3 User profile

In the real world, every apartment has a different user profile, while in this example, specific information has been used to create a basis against which other apartments can be compared. The typical number of users in an apartment is seven, including a housemaid; the average family size is 5.9 members [51], [118]. The activity in the apartment varies depending on the parents' professions. However, in this thesis, it is assumed that user activities are based on a proposed schedule of activities and AC working duration hours, as demonstrated in Table 4.4. Furthermore, every room has a different number of hours during which the AC is used; the living room proved to be the most active room, with usage of 17.5 hours per day, and the guest room was the least active room, using an average of 3 hours per day, as Figure 4.4 illustrates.

TABLE 4.4 User activity schedule for a case model of a Saudi Family.

Activity	Sun.	Mon.	Tues.	Wed.	Thurs.	Fri.	Sat.	Total hours/ room/ week	Total hours/ room/ month	Average hours/ room/ day
Master Bedroom	23:00-06:00	23:00-06:00	23:00-06:00	23:00-06:00	23:00-06:00	23:00-06:00	23:00-06:00	49	210	7
Children's Bedroom 1	21:30-06:00	21:30-06:00	21:30-06:00	21:30-06:00	23:30-08:00	23:30-08:00	21:30-06:00	59.5	255	8.5
Children's Bedroom 2	21:30-06:00	21:30-06:00	21:30-06:00	21:30-06:00	23:30-08:00	23:30-08:00	21:30-06:00	59.5	255	8.5
Housemaid's Bedroom	23:30-07:00	23:30-07:00	23:30-07:00	23:30-07:00	23:30-07:00	23:30-07:00	23:30-07:00	52.5	225	7.5
Dining Room	06:30-07:30	06:30-07:30	06:30-07:30	06:30-07:30	06:30-07:30	06:30-07:30	06:30-07:30	7	120	4
	16:00-17:30	16:00-17:30	16:00-17:30	16:00-17:30	16:00-17:30	16:00-17:30	16:00-17:30	10.5		
	20:30-22:00	20:30-22:00	20:30-22:00	20:30-22:00	21:30-23:00	21:30-23:00	20:30-22:00	10.5		
Living Room	06:00-23:30	06:00-23:30	06:00-23:30	06:00-23:30	06:00-23:30	06:00-23:30	06:00-23:30	122.5	525	17.5
Kitchen	06:00-07:30	06:00-07:30	06:00-07:30	06:00-07:30	06:00-07:30	06:00-07:30	06:00-07:30	10.5	255	8.5
	14:00-18:00	14:00-18:00	14:00-18:00	14:00-18:00	14:00-18:00	14:00-18:00	14:00-18:00	28		
	20:00-23:00	20:00-23:00	20:00-23:00	20:00-23:00	20:00-23:00	20:00-23:00	20:00-23:00	21.00		
Guest Room	None	None	None	None	17:00-24:00	17:00-24:00	17:00-24:00	21	90	3

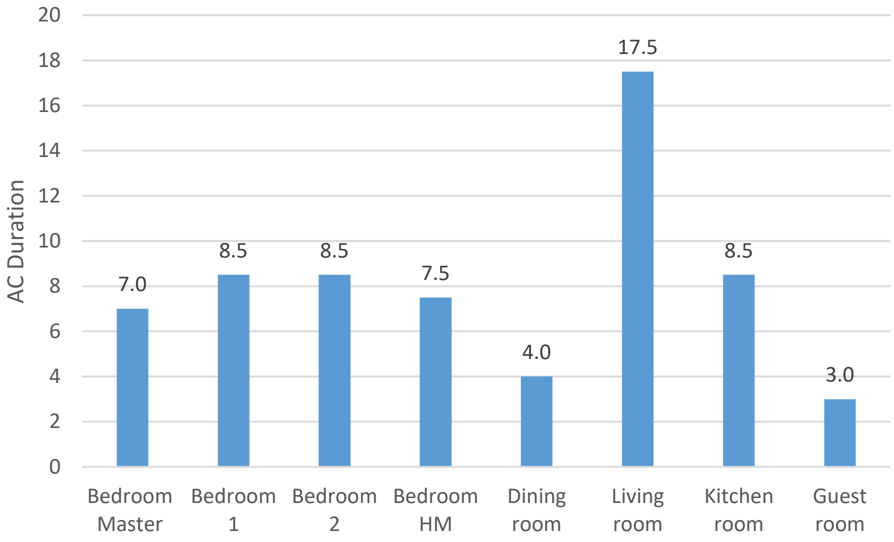

FIG. 4.5 Comparison of the average AC duration for different rooms per day.

The provided assumed activity hours were the minimum duration hours that varied between families. However, a compact schedule, i.e., a schedule where the people who lived in the house were there for the maximum number of hours, was taken as the basis to use later in the simulation program (DesignBuilder). The assumed schedule was applied to all the apartments to provide comparable numbers that could subsequently be validated. The occupancy percentage was 20% during the inactive hours (07:00-16:00).

4.4.4 Building Ownership

The ownership of a residential building was primarily only single ownership until it developed into a multi-ownership model. In 2018, the “Mullak” ownership system was introduced to settle the required rules for single- and especially multi-ownership types of apartments [119]. In this study, the ownership of a building has a significant role in designing the energy retrofitting scenarios, which have been divided into single-ownership or multi-ownership types.

Typically, the construction of any residential building falls within three types of constructors: individual, private developer, or governmental. Each type has different business activities that fulfil the construction’s primary goal. Therefore, the type of ownership falls under single- or multi-ownership, as Table 4.5 illustrates.

TABLE 4.5 Different business activities for several building contractors.

Contractor	Individual	Private Developer	Governmental	Ownership Type
Business Activities	Selling	Selling	Selling	Multi
	Living +Selling			
	Renting for Short Term	Renting for Short Term	Renting for Long Term	Single
	Living + Renting for Short Term			

The energy retrofitting scenarios have been divided into two primary types: indoor and outdoor. The indoor scenarios are possible for both ownership types, while the outdoor scenarios are only possible for the single ownership type because of difficulties in the decision-making processes.

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4.4.5 Simulation Description

The selected software was Design Builder [120], which allows engineer researchers to analyze the energy consumption of building energy. However, a comparative study of widely used dynamic simulation tools for buildings, such as EnergyPlus, TRNSYS, Simulink libraries CarnotUIBK and ALMABuild, IDA ICE, Modelica/Dymola, and DALEC, demonstrated a good consensus among these tools, despite the varying levels of input detail required by each tool [121]. The Design-Builder tool was chosen due to its availability in the market and its accessibility as a simulation software. It allows for the analysis and prediction of energy consumption in any structure using predefined datasets. The Design-Builder program is particularly user-friendly, making it suitable for educational purposes. It eliminates the need to extensively delve into software details and codes. The main features of using the Design-Builder software are its ability to simulate accurate environmental performance data, its fast simulation capabilities, and its ability to import various file types for 2D and 3D imaging. Additionally, one can save rendered images of any result at any stage [60],[61].

The study modelled the case study in the Design Builder software using the collected actual floor plans from the Archteam firm. The data were entered based on previous studies described earlier in this chapter.

Initially, the floor plans were extracted from the provided documents, and a 3D model was constructed using the Design Builder software. The wall specifications were then added based on Table 4.3, which was derived from Table 3.8 and other relevant literature. Subsequently, the window and roof specifications were incorporated. Afterward, various datasets were inputted, including ACH50 (N50), set-point air temperature, climate data, and activity data. The simulation was then conducted to obtain annual energy consumption data, which were stored in an Excel file. The simulation covered 8 apartments, each with 17 scenarios (10 indoor and 7 outdoor), resulting in a total of 272 simulations per trial.

Due to various uncertainties, the simulation was repeated multiple times, accounting for factors such as the actual infiltration rate and the AC setback temperature, which are further elaborated upon in the subsequent sections. Each scenario's simulation time ranged up to 7 s. The primary objective of using AAEC (Annualized Average Energy Consumption) was to compare the energy consumption before and after implementing the upgrading measures for all eight apartments within a single building.

4.5 Energy retrofitting scenario description

The available energy retrofit interventions were described in the previous chapter as a guideline for designing the energy retrofitting scenarios in this section. Table 4.6 illustrates every energy upgrade scenario as it shows the interventions used. The concept achieves high-resolution scenarios by starting with minimal changes and adding additional intervention to reach an efficient scenario that meets the SBC (green labels in Tables 4.7 and 4.8). The design was divided into two categories, indoor scenarios and outdoor scenarios, and these are described as follows.

A Indoor Scenarios

In Table 4.7, Scenario 1 involves the replacement of windows with an energy-efficient option. Scenarios 2-5 incorporate additional measures to enhance wall insulation with local materials to achieve the required SBC U-values. Scenarios 6 and 7 incorporate the wall upgrade aspect of Scenario 5, with the window replacement, while the only difference between Scenarios 6 and 7 is the type of windows used. Scenarios 8 and 9 follow the approach of Scenario 7 and upgrade the roof U-value with two distinct U-values. Finally, Scenario 10 builds upon Scenario 8 and replaces the air-conditioning systems with efficient alternative.

B Outdoor Scenarios

In Table 4.8, Scenarios 1 and 2 incorporate external insulation and finishing systems (EIFSs) as add-on measures to improve the U-value of the walls. Scenarios 3 and 4 build upon Scenario 2 and replace the windows. Scenarios 5 and 6 follow the approach of Scenario 4, including upgrading the roof U-values. Lastly, Scenario 7 incorporates the measures from Scenario 5 but also involves replacing the air-conditioning systems with energy-efficient alternative.

Tables 4.7 and 4.8 demonstrate how and what the scenarios are. The central concept of designing the energy retrofit scenarios was to develop scenarios from a minor upgrade to a deeper upgrade using mixed energy-retrofitting strategies (add-in, add-on, replace-it, and wrap-it) in order to reach the SBC energy requirements. The scenarios are intended to develop the targeted envelope component (wall, windows, and roof) to upgrade the heat-resistant value in order to achieve better performance.

In addition, Tables 4.7 and 4.8 illustrate the scenarios designed to achieve the SBC requirements, where red colors mean that the value did not meet the SBC energy requirements, while green means that the value did meet the SBC energy requirements.

TABLE 4.6 Overview of indoor and outdoor scenarios. Detail for the scenario construction in Tables 4.7 and 4.8. : HFC (a type of XPS insulation in Design builder)

Indoor Scenarios	
Base Case	Base case Corner face SW +SB+ACH50 4
Scenario 1	Mortar Finishing + Replace Windows (Creative Windows CO.)
Scenario 2	Wall (EPS 5cm)+ Cement Hollow Block (10cm)+ Mortar Finishing
Scenario 3	Wall (XPS 5cm)(HFC)+ Mortar Finishing
Scenario 4	Wall (XPS 7.5cm)(HFC)+ Mortar Finishing
Scenario 5	Wall (XPS 10 cm)(HFC)+ Mortar Finishing
Scenario 6	Wall (XPS 10 cm)(HFC)+ Mortar Finishing + Replace Windows (Wintek HD Plus Gray)
Scenario 7	Wall (XPS 10 cm)(HFC)+ Mortar Finishing + Replace Windows (Creative Windows CO.)
Scenario 8	Wall (XPS 10 cm)(HFC)+Mortar Finishing + Replace Windows (Creative Windows CO.) +Roof XPS 10cm
Scenario 9	Wall (XPS 10 cm)(HFC)+Mortar Finishing + Replace Windows (Creative Windows CO.) + Upgrade Roof with XPS 15cm
Scenario 10	Wall (XPS 10 cm)(HFC)+Mortar Finishing + Replace Windows (Creative Windows CO.) + Upgrade Roof with XPS 10cm + Replace ACs with COP 4
Outdoor Scenarios	
Base Case	Base Case Corner Face SW +SB
Scenario 1	EIFS Wall (EPS 10cm)
Scenario 2	EIFS Wall (XPS 10cm)
Scenario 3	EIFS Wall (XPS 10cm)+ Replace Windows Wintek HD Plus Grey
Scenario 4	EIFS Wall (XPS 10cm)+ Replace Windows (Creative Windows CO.)
Scenario 5	EIFS Wall (XPS 10cm)+ Replace Windows (Creative Windows CO.) + Upgrade Roof with XPS 10cm
Scenario 6	EIFS Wall (XPS 10cm)+ Replace Windows (Creative Windows CO.) + Upgrade Roof with XPS 15cm
Scenario 7	EIFS Wall (XPS 10cm)+ Replace Windows (Creative Windows CO.) + Upgrade Roof XPS 10cm + Replace ACs with COP 4

TABLE 4.7 Indoor energy retrofit scenarios for a residential building in Jeddah (red color indicates didn't meet the SBC and green color indicates the value meet the SBC).

	Base Case	Scen. 1	Scen. 2	Scen. 3	Scen. 4	Scen. 5	Scen. 6	Scen. 7	Scen. 8	Scen. 9	Scen. 10
N50 (ACH50)	20.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
Wall U-Value (W/m^{2}K)	2.68	2.68	0.53	0.49	0.35	0.27	0.27	0.27	0.27	0.27	0.27
Thickness (m)	0.24	0.24	0.39	0.29	0.32	0.34	0.34	0.34	0.34	0.34	0.34
Roof U-Value (W/m^{2}K)	2.81	2.81	2.81	2.81	2.81	2.81	2.81	2.81	0.27	0.19	0.27
Thickness (m)	0.345	0.345	0.345	0.345	0.345	0.345	0.345	0.345	0.445	0.495	0.445
G-Floor U-Value (W/m^{2}K)	2.27	2.27	2.27	2.27	2.27	2.27	2.27	2.27	2.27	2.27	2.27
Thickness (m)	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44
R-Floor U-Value (W/m^{2}K)	2.40	2.40	2.40	2.40	2.40	2.40	2.40	2.40	2.40	2.40	2.40
Thickness (m)	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
Window Glazing Type	Single 3mm	6mm-12mm air-6mm	Single 3mm	Single 3mm	Single 3mm	Single 3mm	6mm-12mm air-6mm	6mm-12mm air-6mm	6mm-12mm air-6mm	6mm-12mm air-6mm	6mm-12mm air-6mm
Window Glazing U-value (W/m^{2}K)	5.89	2.13	5.89	5.89	5.89	5.89	2.69	2.13	2.13	2.13	2.13
Glazing Type	Clear	Gray reflective SHANGHAI	Clear	Clear	Clear	Clear	Gray hd plus	Gray reflective SHANGHAI	Gray reflective SHANGHAI	Gray reflective SHANGHAI	Gray reflective SHANGHAI
Window Glazing (SHGC)	0.86	0.25	0.86	0.86	0.86	0.86	0.25	0.25	0.25	0.25	0.25
Window Frame Type	Aluminum	UPVC Creative Windows	Aluminum	Aluminum	Aluminum	Aluminum	UPVC wintek	UPVC Creative Windows	UPVC Creative Windows	UPVC Creative Windows	UPVC Creative Windows
Window Frame U-Value (W/m^{2}K)	5.88	1.33	5.88	5.88	5.88	5.88	1.79	1.33	1.33	1.33	1.33
Window Ratio (WWR)	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Lighting W/m2-100lux	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
AC type	AC Window	AC Window	AC Window	AC Window	AC Window	AC Window	AC Window	AC Window	AC Window	AC Window	AC Split
(CoP)	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	4.00

TABLE 4.8 Outdoor energy retrofit scenarios for a residential building in Jeddah (red color indicates didn't meet the SBC and green color indicates the value meet the SBC).

	Base Case	Scen. 1	Scen. 2	Scen. 3	Scen. 4	Scen. 5	Scen. 6	Scen. 7
N50 (ACH50)	20.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
Wall (U-value) (W/m²K)	2.68	0.31	0.27	0.27	0.27	0.27	0.27	0.27
Thickness (m)	0.24	0.36	0.36	0.36	0.36	0.36	0.36	0.36
Roof (U-value) (W/m²K)	2.81	2.81	2.81	2.81	2.81	0.27	0.19	0.27
Thickness (m)	0.35	0.35	0.35	0.35	0.35	0.45	0.50	0.45
G-Floor (U-value) (W/m²K)	2.27	2.27	2.27	2.27	2.27	2.27	2.27	2.27
Thickness (m)	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44
R-Floor (U-value) (W/m²K)	2.40	2.40	2.40	2.40	2.40	2.40	2.40	2.40
Thickness (m)	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
Window Glazing Type	Single 3mm	Single 3mm	Single 3mm	6mm-12mm air-6mm	6mm-12mm air-6mm	6mm-12mm air-6mm	6mm-12mm air-6mm	6mm-12mm air-6mm
Window Glazing (U-value) (W/m²K)	5.89	5.89	5.89	2.69	2.13	2.13	2.13	2.13
Glazing Type	Clear	Clear	Clear	Gray hd plus	Gray reflective SHANGHAI	Gray reflective SHANGHAI	Gray reflective SHANGHAI	Gray reflective SHANGHAI
Window Glazing (SHGC)	0.86	0.86	0.86	0.25	0.25	0.25	0.25	0.25
Window Frame Type	Aluminum	Aluminum	Aluminum	UPVC wintek	UPVC Creative Windows	UPVC Creative Windows	UPVC Creative Windows	UPVC Creative Windows
Window Frame (U-value) (W/m²K)	5.88	5.88	5.88	1.79	1.33	1.33	1.33	1.33
Window Ratio (WWR)	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Lighting W/m2-100lux	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
AC type	AC Window	AC Window	AC Window	AC Window	AC Window	AC Window	AC Window	AC Split
(CoP)	1.80	1.80	1.80	1.80	1.80	1.80	1.80	4.00

The infiltration rate was assumed as 20 ACH50, as recommended by Makawi, where higher results could be possible for the basic case [97], [123]. The rationale for employing a value of 20 ACH50 to represent infiltration in simulation software is based on several factors. ASHRAE defines infiltration as the unintended flow of outdoor air into a building through cracks, openings, and exterior doors [123]. Airtightness is a related concept, referring to the amount of air infiltrating a building at a pressure difference of 50 Pa [124]. Infiltration and airtightness are distinct but related phenomena, with empirical evidence suggesting that infiltration is typically around 1/20th the value of airtightness [124].

The blower door test (BDT) is commonly used to measure airtightness by measuring air change rates under a 50 Pa pressure difference [123]. The resulting value, known as ACH50, is a measure of the infiltration of outdoor air into a building and is influenced by envelope tightness. Infiltration can contribute significantly to a building's heating and cooling loads, with estimates ranging from 25% to 50% in some studies [125], [126]. Research has shown a wide range of ACH50 values in residential buildings, with values as high as 39 ACH50 in some cases [127]. However, the exact value will vary depending on various factors, including the type of window frames used.

In Saudi Arabia, a study found a lack of infiltration data on the building stock and recorded ACH50 values of 6.58 and 7.04 for two houses in Dhahran City [123]. These values were due to exfiltration caused by the central HVAC fan system. This study and other literature show that 20 ACH50 is not considered high for an existing residential building.

To validate the proposed energy retrofitting scenarios, a value of 20 ACH50 is used for the basic case model to improve this value to 4 ACH50, as required by the Saudi Building Code for the airtightness of residential buildings in Jeddah. This approach aligns with previous research recommendations and is based on a range of empirical evidence.

4.6 Results and Analysis

The energy performance simulation process follows three steps. The first step explores the highest average energy consumption of a residential building using different urban positions. The second step shows the different energy consumption results when the variables have been changed, such as the infiltration rate or how the temperature in the various rooms is controlled, which will later affect the possible energy-saving results. The third step involves performing an energy simulation for each proposed scenario in order to calculate the potential energy savings. Hence, every step will provide significant information that will help analyze the simulation results using different variables.

4.6.1 Step one: Building position (locating the highest energy consumption)

In the KSA context, it is possible for a residential building to be situated in six different positions when the alone (no surrounding buildings) position faces towards the south (see Figure 4.6) or the north position is found to have almost the same average AAEC as 180 kWh/m²/year for both positions, as shown in Figures 4.8 and 4.9. The south-west (SW) position (see Figure 4.7 for positioning) recorded the highest AAEC compared to other positions, as shown in Figure 4.8.

Note that the apartments switched sides when the building switched from north to south orientation. At the apartment level, the AAEC increased from ground-level to top-floor apartments requiring additional energy-saving interventions in the designing stage (see Figures 4.8 and 4.9).

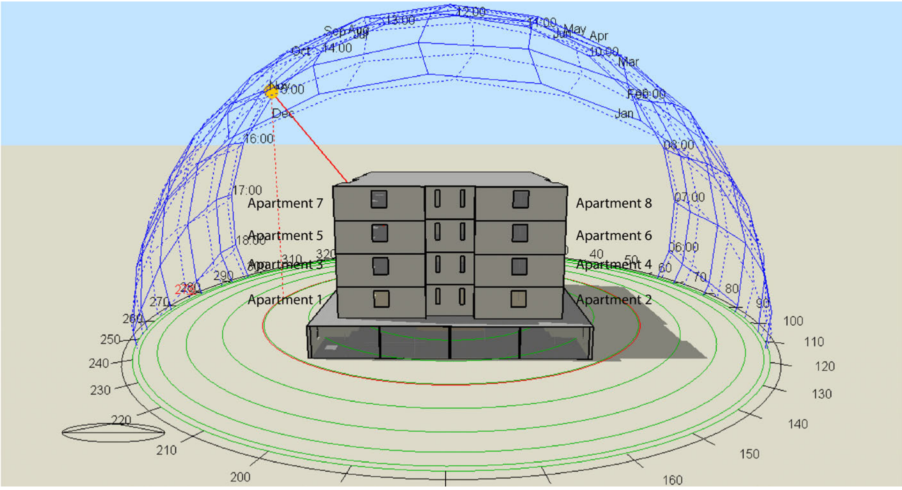

FIG. 4.6 Rendering of a residential building (south orientation).

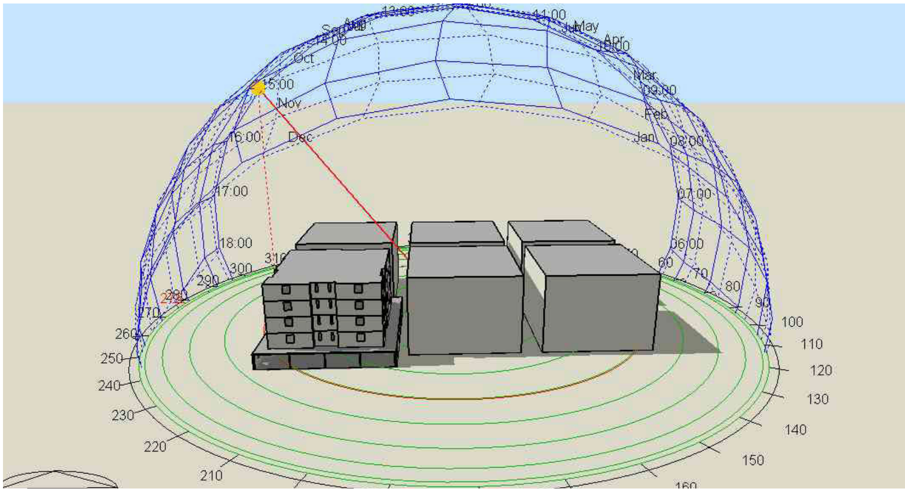

FIG. 4.7 Rendering of a residential building (south-west orientation) within other buildings.

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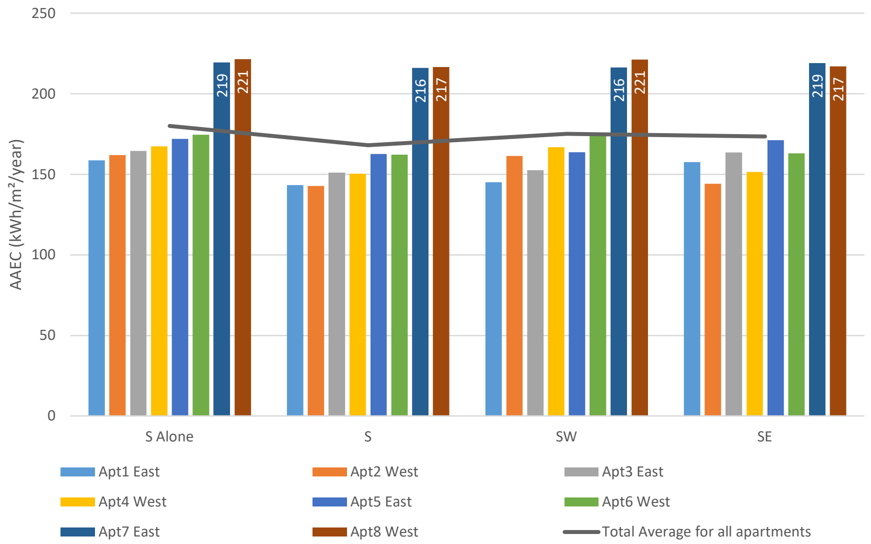

FIG. 4.8 Comparison of energy consumption for different building positions that face south Note: S Alone (building position_ Facing south alone with no surroundings buildings.

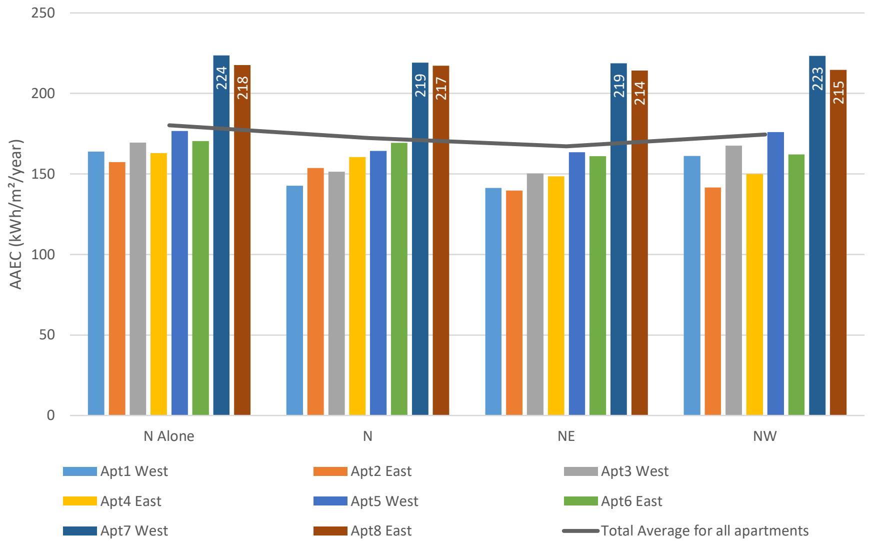

FIG. 4.9 Comparison of energy consumption for different building positions that face north. Note: N Alone (building Facing North alone with no surroundings buildings).

4.6.2 Step two: Effect of changing infiltration rate and cooling temperature on AAEC

The infiltration rate ACH50 is crucial in determining the AAEC. In this study, ACH50 values of 4, 6, 7, 8, 15, 30, and 50 were considered, with 4 ACH50 considered best practice according to the SBC [6]. The maximum ACH50 value of 50 was determined based on previous studies that found a maximum of 39 ACH50 through monitoring methods [127]. This study includes the infiltration rate and its impact on the AAEC, with results demonstrating the significance of the ACH50 on energy consumption for each scenario and apartment. The study used 20 ACH50, calibrated with the average energy consumption bill as reported by Aldossary for the first two floors of the building [30]. Hence, different infiltration rates (50 to 4 ACH50) were tested and, when applying lower infiltration rates, lower AAEC results were achieved. Figure 4.10 demonstrates a range of decreases in AAEC when only changing the infiltration rate from 50 to 4 within the same apartment. The Figure shows a decrease in AAEC percentages ranging from 26% to 38% for 4 ACH50, and ranging from 11% to 17% for ACH30 compared to the ACH50 rate. Top-floor apartments with higher ACH50 values exhibited the highest rates when compared to lower-floor apartments. However, the decrease in ACH50 rates has a greater impact on lower-floor apartments compared to upper-floor apartments.

The user comfort level is another factor affecting the AAEC, as cooler temperatures increase energy consumption, requiring extra cooling. The thermal comfort preferences of occupants in Jeddah vary, with a typical cooling temperature range of 19-24°C, according to Felimban [41]. The scenarios for changing cooling temperatures highlight the impact on the AAEC. For example, as shown in Figure 4.11, the AAEC for apartment 1 decreases by approximately 4 kWh/m^2/year when the cooling temperature is increased by 1°C. However, decreasing the cooling temperature by 2 or 3°C increases the AAEC by around 15, 33, or 51 kWh/m^2/year. However, a lower cooling set-point temperature leads to a higher AAEC in air-conditioned apartments. To conclude, both the infiltration rate and user thermal comfort levels are considered primary impact factors that contribute to the increase or decrease in the AAEC, as shown in Figures 4.10 and 4.11.

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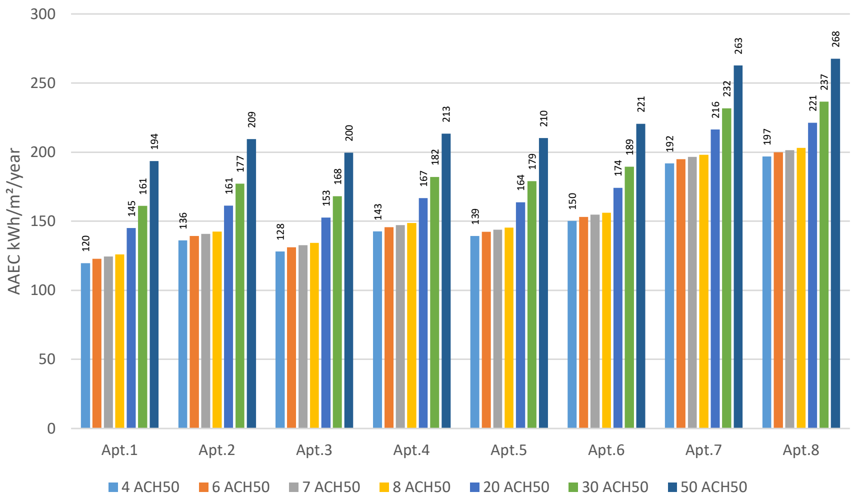

FIG. 4.10 Changes in the impact of the ACH50 rate on AAEC for every apartment.

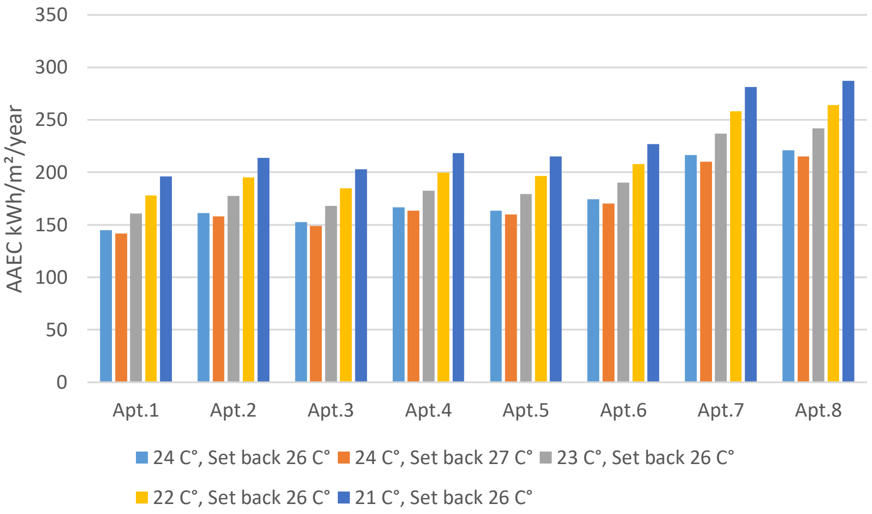

FIG. 4.11 Impact of changing the setback point of the cooling temperature on AAEC using DesignBuilder simulation.

4.6.3 Step three: Energy performance simulation and energy savings

The energy simulation of the basic model used 20 ACH50 infiltration rates and aimed to produce scenarios targeting a rate of 4 ACH50 as the SBC standards require. According to the simulation results, Figures 4.12, 4.13, 4.17, and 4.18 illustrate the AAEC for each apartment using infiltration rates of 20 and 4 ACH50. The following two sections illustrate the AAEC results that depend on the user scenario and the selected infiltration rate. The simulation was divided into indoor and outdoor scenarios, as explained earlier in the description of the scenarios.

A Indoor Scenarios

As previously explained, indoor scenarios can be applied individually to any apartment. The simulation results show an extensive reduction in AAEC when using a deep energy retrofit scenario (Scenario 10); the reduction was up to 121 kWh/m²/year. When applying a minor retrofit scenario (Scenario 2), it was possible to reduce the amount of electricity used by at least 34 kWh/m²/year compared to the basic model. In addition, the AAEC varied from one apartment to another depending on the apartment position (floor level) and the apartment orientation in the building. All of the deep retrofit scenarios led to a more efficient AAEC for all apartments.

The most critical factor of AAEC reduction was the insulation upgrades for the walls and roofs. Adding an insulation layer to the walls and roof (scenarios 2-10) resulted in a significant sharp reduction in energy use, as shown in Figures 4.12 and 4.13. For instance, in Apartment 1, the AAEC for the base case was just below 150 kWh/m²/year, while Scenarios 2-5 recorded around 100 kWh/m²/year. This represents a reduction of around 30% in AAEC by adding just wall insulation. In the same apartment, implementing window replacement and roof insulation (Scenarios 6-9) would result in a further reduction of approximately 45% in AAEC. Therefore, wall upgrades yield greater benefits for apartments on the lower floors, whereas roof upgrades are particularly effective for those on the upper floors.

Energy savings gradually increased from Scenario 1 (5%-10%) to Scenario 10 (45%-56%), where the infiltration rate was 20 ACH50, while for the 4 ACH50 infiltration rate, Scenario 1 (6%-12%) to Scenario 10 (55%-65%) are illustrated in Figures 4.14 and 4.15. There were remarkable differences in energy savings between apartments when applying the different Scenarios (1, 2-5, 6-7, and 8-10).

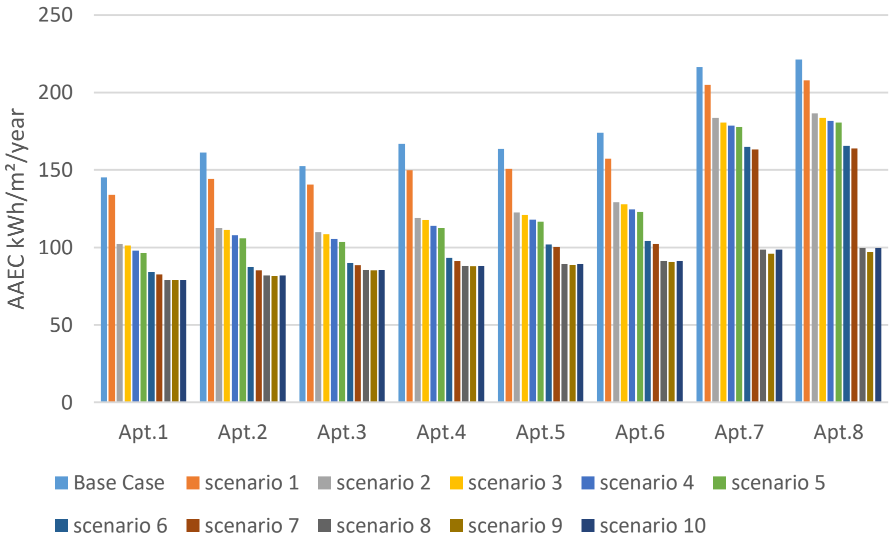

FIG. 4.12 AAEC values for indoor energy retrofitting scenarios using 20 ACH50 for infiltration rate, with a rate of 20 ACH50 for the basic model.

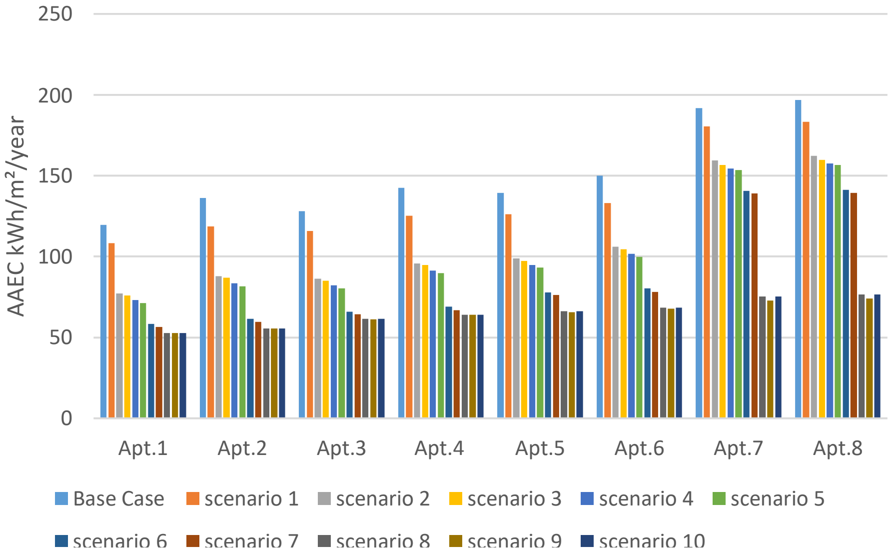

FIG. 4.13 AAEC values for indoor energy retrofitting scenarios using 4 ACH50 for infiltration rate, with a rate of 20 ACH50 for the basic model.

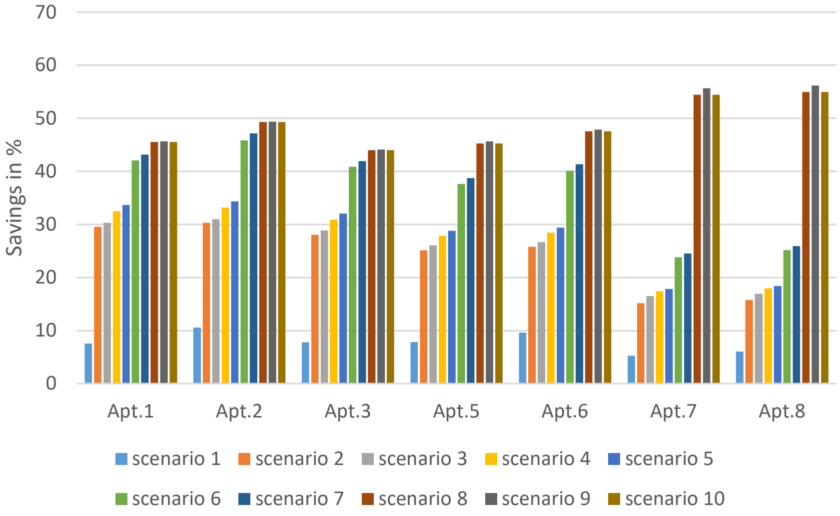

FIG. 4.14 Possible energy savings percentages from testing different scenarios (indoor) where the infiltration rate is 20 ACH50, with a rate of 20 ACH50 for the basic model.

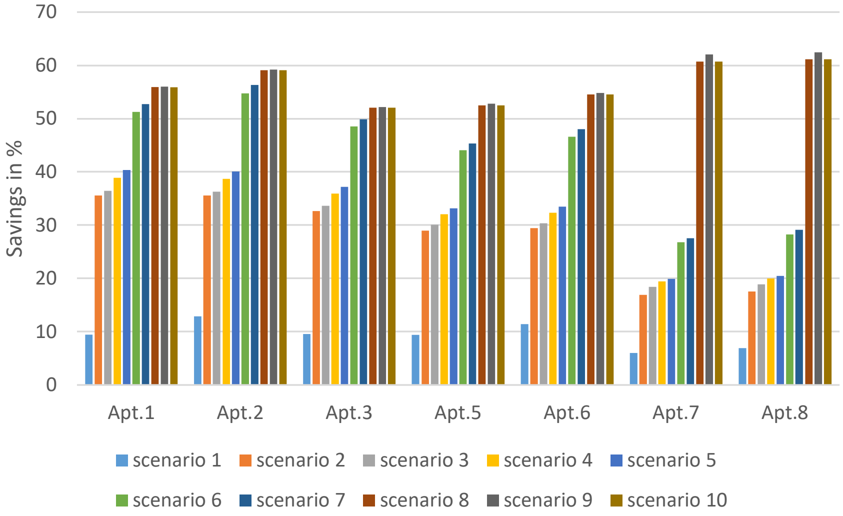

FIG. 4.15 Possible energy savings percentages from testing different scenarios (indoor) where the infiltration rate is 4 ACH50, with a rate of 4 ACH50 for the basic model

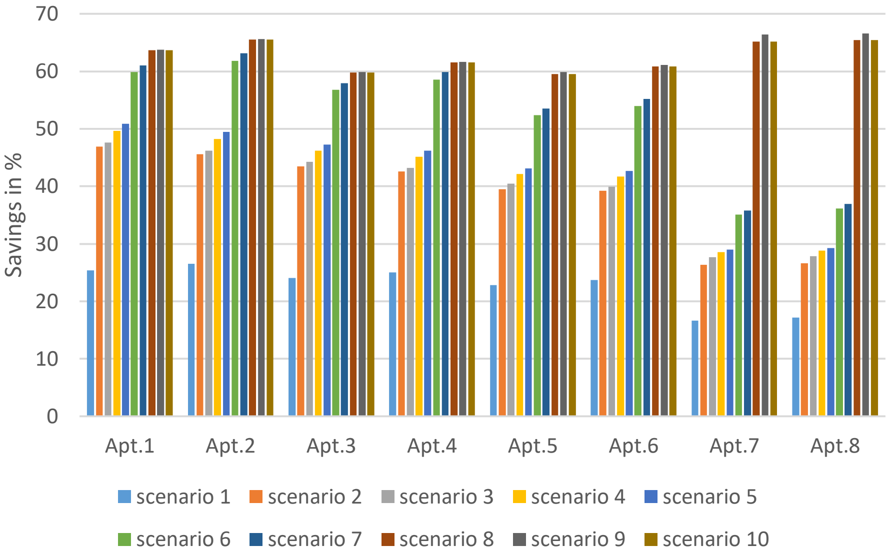

FIG. 4.16 Possible energy savings from testing different scenarios (indoor) where the infiltration rate is 4 ACH50, with a rate of 20 ACH50 for the basic model.

Apartments 7 and 8 recorded around 60% savings when using Scenarios 8, 9, and 10, where additional insulation was added to the roofs. However, apartments 1-6 only had a slight savings increase when applying Scenarios 8, 9, and 10 compared to Scenarios 6 and 7. Apartments 7 and 8 had less energy savings than apartments 1-6 when using Scenarios 1-7. Therefore, it is suggested that every apartment has specific properties that require different energy retrofitting scenarios, and an individual cost analysis per apartment is required.

Furthermore, more energy savings were achieved when the basic model used 20 ACH50 and the applied scenarios used 4 ACH50. The energy savings increased for Scenario 1 from 5%-10% to 17%-26%, and for Scenario 10 they increased from 45%-56% to 63%-65%, where the change in the ACH50 rate had a significant impact on the energy savings percentage (see Figure 4.16). The considerable energy savings show the importance of considering infiltration rate levels in energy retrofitting applications to achieve a better AAEC for all apartments.

The indoor scenarios are very valuable for individual decision-making for energy retrofit upgrades. The only concern in these indoor scenarios is the thermal heat transfers through the concrete skeleton structure (thermal bridges), especially when the structure intersects with an indoor partition. In this thesis, thermal bridges (heat transfer) have not been incorporated in the calculations, as the main objective of the study was to calculate the overall energy savings possibilities so that the factors could be easily calculated in future in order to help retrofit the residential buildings and ensure energy efficiency.

In summary, the indoor scenarios of energy retrofitting applications have great potential to enhance the energy efficiency of residential apartments, with energy savings ranging from 20% to 65% depending on the apartment's circumstances.

B Outdoor Scenarios

The outdoor scenarios, as observed earlier, can only be applied to the whole building and cannot be applied to individual upgrades to individual apartments. The simulation results show a sharp reduction in AAEC when using a deep energy retrofit scenario, as can be seen with Scenario 10 shown in Figures 4.17 and 4.18. However, adding 10 cm of insulation to the outdoor wall, as shown in Scenario 1, can significantly reduce at least 50 kWh/m²/year compared to the basic model. Figures 4.17 and 4.18 illustrate significant reductions in AAEC, each using different infiltration rates of 20 ACH50 and 4 ACH50.

To provide more detail, Figure 4.17 presents different ranges of decrease of the AAEC depending on the apartment and the applied scenario. The AAEC results for apartment 1 show a 33% reduction for Scenario 1 and a 46% reduction for Scenario 7. However, apartment 8 records an 18% reduction for Scenario 1 and a 55% reduction for Scenario 7.

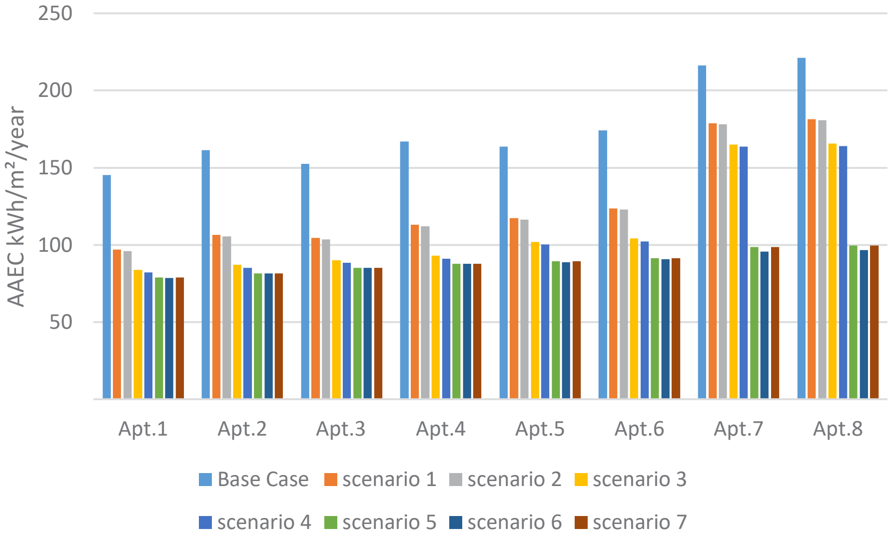

FIG. 4.17 AAEC for outdoor energy retrofitting scenarios using 20 ACH50 for the infiltration rate, with a rate of 20 ACH50 for the basic model.

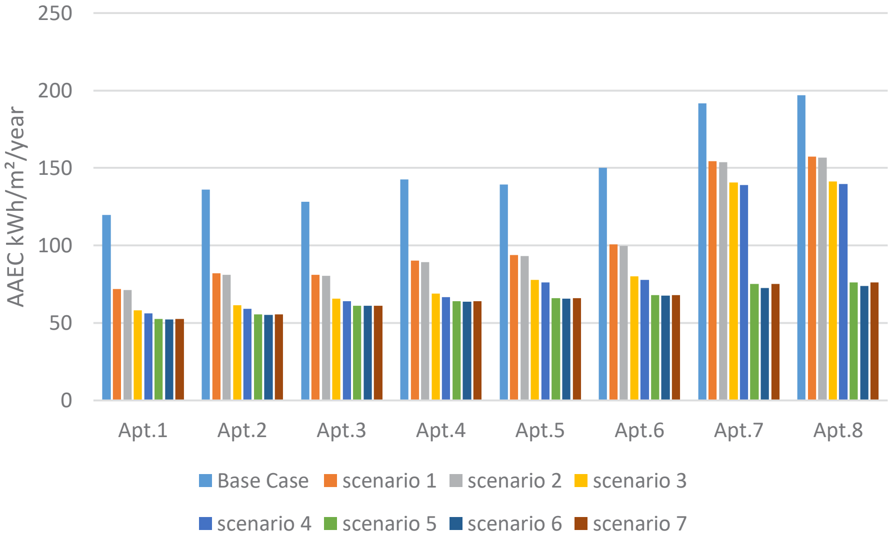

FIG. 4.18 AAEC for outdoor energy retrofitting scenarios using 4 ACH50 for the infiltration rate, with a rate of 4 ACH50 for the basic model.

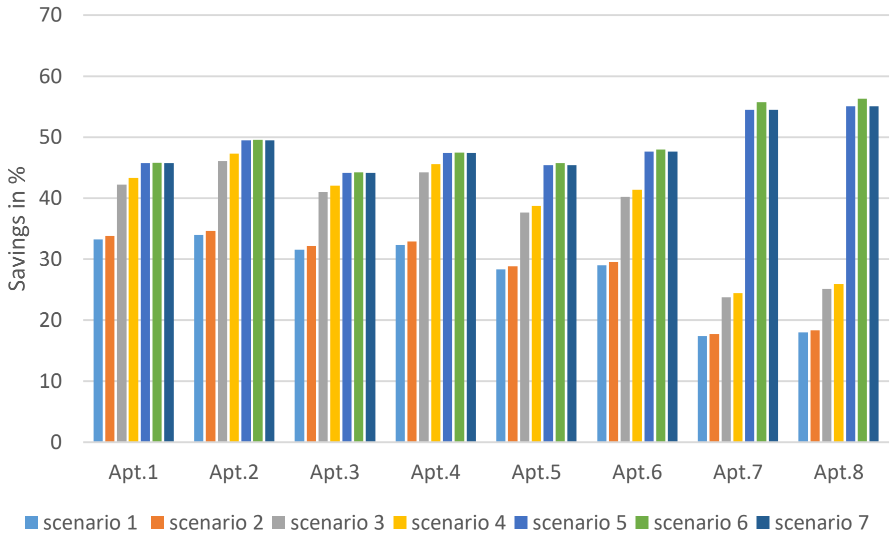

FIG. 4.19 Possible energy savings from testing different outdoor scenarios where the infiltration rate is 20 ACH50, with a rate of 20 ACH50 for the basic model.

Apartments 1-6 gradually increased their energy savings when applying the scenarios in order, as Figures 4.19 and 4.20 illustrate. Apartments 7 and 8 had less energy savings when using Scenarios 1-4 compared to the other apartments. However, outdoor Scenarios 5-7 significantly increased the energy savings for apartments 7 and 8. Generally, the high-resolution scenarios depend on the infiltration rate levels and the selected scenario.

Figure 4.21 indicates more promising energy savings for all units when applying scenarios that include improving the infiltration rate to 4 ACH50 compared to the results in Figure 4.20. Figure 4.21 shows decreasing savings percentages from 50% to around 30% for apartments 1 and 8, respectively. However, if any of Scenarios 5-7 applied to all apartments 1, 2, 3, 4, 5, 6, 7, and 8, then AAEC could reach efficient consumption values of 52, 55, 61, 63,66, 68, 75, and 76 kWh/m²/year, respectively.

In summary, the simulation results for the energy performance of a residential building in Jeddah indicate an optimistic range of energy savings (30%-60%) when various energy retrofit scenarios are applied, taking into account improvements in the infiltration rate.

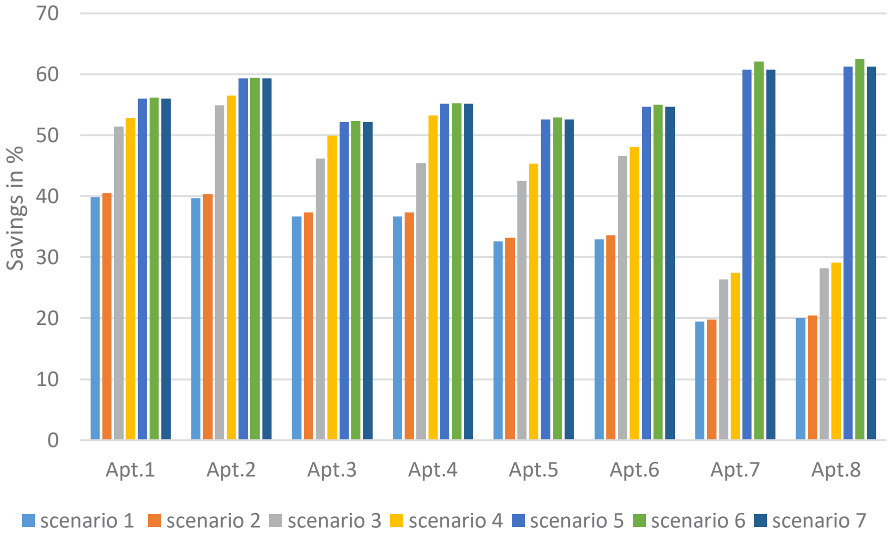

FIG. 4.20 Possible energy savings from testing different scenarios (outdoor) where the infiltration rate is 4 ACH50, with a rate of 4 ACH50 for the basic model.

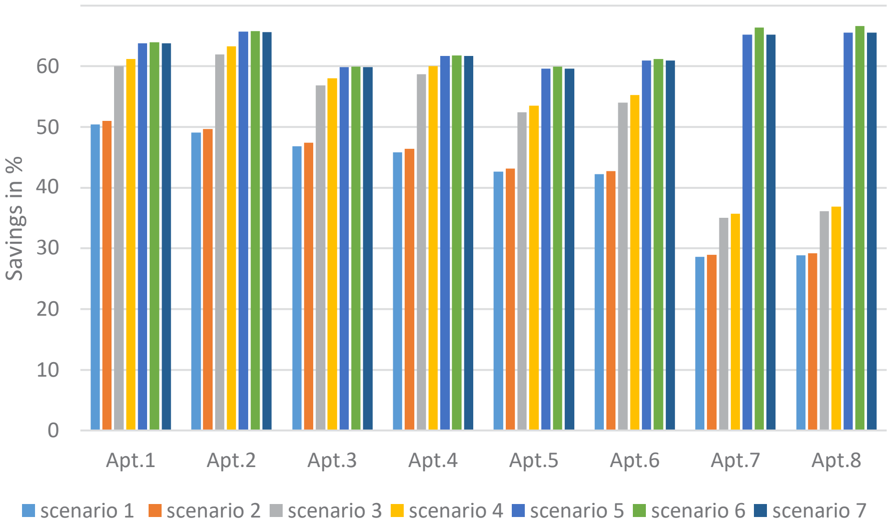

FIG. 4.21 Possible energy savings from testing different scenarios (outdoor) where the infiltration rate is 4 ACH50, with a rate of 20 ACH50 for the basic model.

4.7 Discussion

The discussion has been divided into three main points. Initially, the AAEC is discussed in respect of the eight apartments based on the analyzed properties; secondly, the energy savings possibilities are discussed in respect of applying different scenarios; finally, the uncertainties and the effects on the AAEC are addressed, such as the infiltration rate (ACH50) and the user thermal comfort temperature.

4.7.1 Annual Average Energy Consumption

The simulation results for residential apartments range from 145 to 221 kWh/m²/year, depending on the orientation and the floor level. Apartments situated on the upper floors consume more AAEC than apartments found lower in the building due to the heat exposure from the roof. For instance, apartments 7 and 8 recorded the highest AAEC of 216 and 221 kWh/m²/year.

The apartments that faced the west recorded higher AAEC than east-facing apartments when they were located on the same floor. In addition, two west-facing apartments, i.e., apartments 2 and 4 (161, 166 kWh/m²/year), consumed more than the upper floor, east-facing apartments 3 and 5 (152, 163 kWh/m²/year). The apartment location, specifically the orientation and floor level, are the main factors used to calculate the AAEC.

4.7.2 Energy savings possibilities

In general, the simulation results demonstrate a significant impact from each scenario. The degree of impact is determined by the specific upgrading measures applied to envelope components, such as the walls, windows, or roof. Furthermore, in respect of apartments 1-6, the weaknesses came from the walls and the windows, where different energy savings were recorded from Scenarios 1-7 ranging from 7% to 47%, whereas Scenarios 8-10 only add about 2% savings compared to Scenario 7.

The weaknesses in apartments 7 and 8 were due to all components, and the roof presented the main weakness. For instance, apartment 8 had energy savings when applying Scenarios 1-7 ranging from 6% to 26% and 55% to 56% for Scenarios 8-10.

Every scenario has energy savings possibilities, leading to better energy performance to achieve the main objective of extensive simulation validation.

4.7.3 Uncertainties

Uncertainty factors affect the AAEC, such as the actual infiltration rate and the user's thermal preferences (user thermal comfort). Each factor dramatically influences the AAEC as they can increase the energy savings possibilities when they are known before designing the possible energy scenarios.

An actual infiltration rate (ACH50) is a significant factor that can be used to demonstrate actual energy savings, as Figure 4.22 illustrates. It is also important to note that the savings percentage increased when the infiltration rate was enhanced.

The existing residential buildings in Jeddah, KSA, currently require an air conditioning system every day of the year when an infiltration procedure occurs. If the infiltration rate is tested, then the air tightness of the indoor spaces could be designed better in the energy retrofitting scenarios.

The other factor is the difference in user thermal comfort. User thermal comfort varies from family to family. However, both the infiltration rate and cooling temperature affect the increasing possibility of AAEC for all apartments, as Figure 4.23 illustrates. Understanding the user's thermal comfort would help designers and occupants to lower their energy usage; increasing designers' awareness so that thermal comfort is considered in the design process is very important. In short, higher cooling temperatures and lower infiltration rates lead to extensive energy savings.

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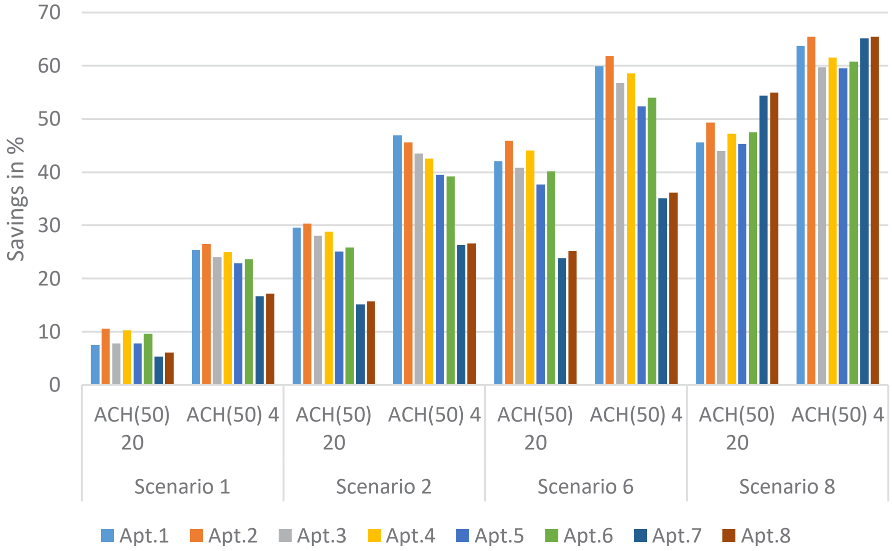

FIG. 4.22 Possible energy savings when different infiltration rates were applied for indoor scenarios

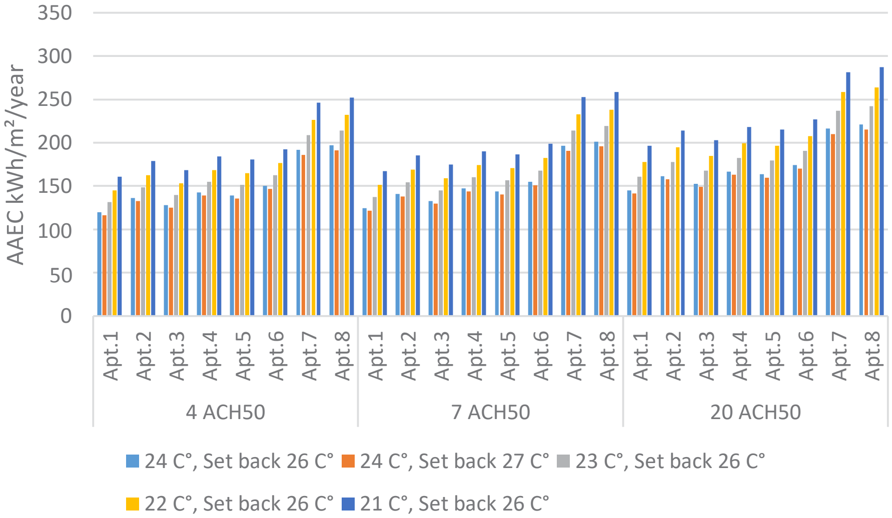

FIG. 4.23 Impacts of cooling temperature and infiltration rate change on AAEC for all apartments for an indoor scenario.

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4.8 Conclusions

The energy retrofit scenarios in this study were validated through the digital simulation process using DesignBuilder software to illustrate the energy savings possibilities. The basic case model results show AAEC values for apartments 1, 2, 3, 4, 5, 6, 7 and 8, respectively, of 145, 161, 152, 166, 163, 174, 216, and 221 kWh/m²/year. However, the building's position within the urban environment affects the AAEC for all units. In the same context, the apartment position (orientation and floor level) leads to a different AAEC for each position.

This chapter has described a case study encompassing essential elements such as building location, apartment positioning, user profiles, and ownership types. Subsequently, two energy-upgrade scenarios (indoor and outdoor) were presented for the eight apartments. The tested energy scenarios focused on upgrading the building components (walls, windows, and roofs) to meet the energy benchmark level (the upgraded SBC energy standards). The chapter comprehensively analyzed the outcomes and elucidated key variables that have the potential to impact energy savings. The results encompass a spectrum of energy-saving possibilities, highlighting that attaining the highest energy savings is contingent upon various factors, including interventions for upgrading the building envelope, enhancements in the infiltration rate, and the targeted level of thermal comfort. The simulation included different design variables, but two main variables (infiltration and user thermal comfort level) could result in a more accurate AAEC if they are known before designing the scenarios.

However, the sole criterion in selecting the optimal scenario was the percentage of energy savings, with the premise being that higher energy savings are preferable. Nonetheless, this chapter has examined energy savings, but evaluating each scenario's cost is also imperative in determining its suitability for individual cases. This aspect will be described in greater detail in the subsequent chapter.

To conclude, based on the analysis for energy retrofit scenarios in Jeddah, a series of simulations was undertaken to confirm energy savings possibilities that could result in a range of energy savings from 25% to 66%.

5 Cost-Benefit Analysis of Energy-Retrofitting Strategy Application

Upgrading the Envelope of Existing (Mid-Rise) Residential Buildings in Jeddah

Chapter 4 validated different energy savings possibilities; however, the cost constraints of ERAs need further analysis. Therefore, Chapter 5 provides a cost–benefit analysis in relation to ERAs using the scenarios from Chapter 4, and suggests those for whom ERAs are beneficial. The chapter also outlines different sources of investment and different payback possibilities. The chapter highlights the most promising investment alternatives to ERAs for the residential buildings in Jeddah city.

Firstly, Section 5.1 introduces the importance of economic analysis of ER within the KSA context. Then, Section 5.2 presents the method used in chapter 5. Next, Section 5.3 indicates the required costs, such as current energy, initial ER, and maintenance costs. Then, Section 5.4 provides calculations for the total cost of each scenario considering the ownership and the apartments' positions. Subsequently, Section 5.5 illustrates eight alternative payback possibilities that depend on investment source options (with and without interests) and payback opportunities (energy savings, oil savings, energy tariff increases, and interest rates). Finally, Section 5.6 discusses the alternatives that are more suitable and beneficial to the state.

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5.1 Introduction

Implementing energy retrofitting strategies in buildings is crucial to improve their energy performance [128]. The main objective of energy retrofitting studies is to reduce energy demand and maximize energy performance. In the Kingdom of Saudi Arabia (KSA), energy retrofitting measures have not been well recognized until recently, owing to the introduction of energy efficiency measures in 2018. During this time, electricity prices increased significantly, while the upgraded Saudi Building Code (SBC) mandated minimum levels of energy efficiency for new constructions [129]. However, existing residential buildings continue to consume substantial energy, necessitating the need for energy retrofitting [29], [30], [130].

Given that current energy retrofit rates in most major markets remain below 1%, energy retrofitting applications are of utmost importance globally [131]. Financial aspects are often the biggest challenges in energy retrofitting applications, including investment availability and payback [36]. This thesis focuses on the economic aspects of energy retrofitting, specifically investment costs, financial savings, and payback periods.

In the KSA, adopting energy retrofitting applications would positively impact the building market and the country’s economy, as elaborated in the upcoming chapter. The primary objective of this chapter is to offer insights into economic feasibility that could be leveraged to implement energy retrofitting applications for existing buildings in Jeddah. Economic variables influence energy retrofitting applications, including investment costs and financial savings from improved energy performance. The economic variables regulate the possible payback alternatives, which will be discussed in detail in subsequent sections.

The outcomes of this study will enable the determination and comparison of appropriate investment payback alternatives for the scenarios described in previous chapters. The payback periods of these alternatives are critical given the Saudi 2030 Vision and the recent focus on achieving net-zero buildings by 2060 [72], [132]. The primary aim of this chapter is to provide an overview of investment considerations and identify proposed payback alternatives, focusing on options that offer the shortest payback periods and promising financial savings.

5.2 Methodology

Chapter 5 presents a quantitative evaluation of the economic feasibility of energy retrofitting applications for existing mid-rise residential buildings in Jeddah. The assessment utilizes the simple payback time (SPT) calculation method [133].

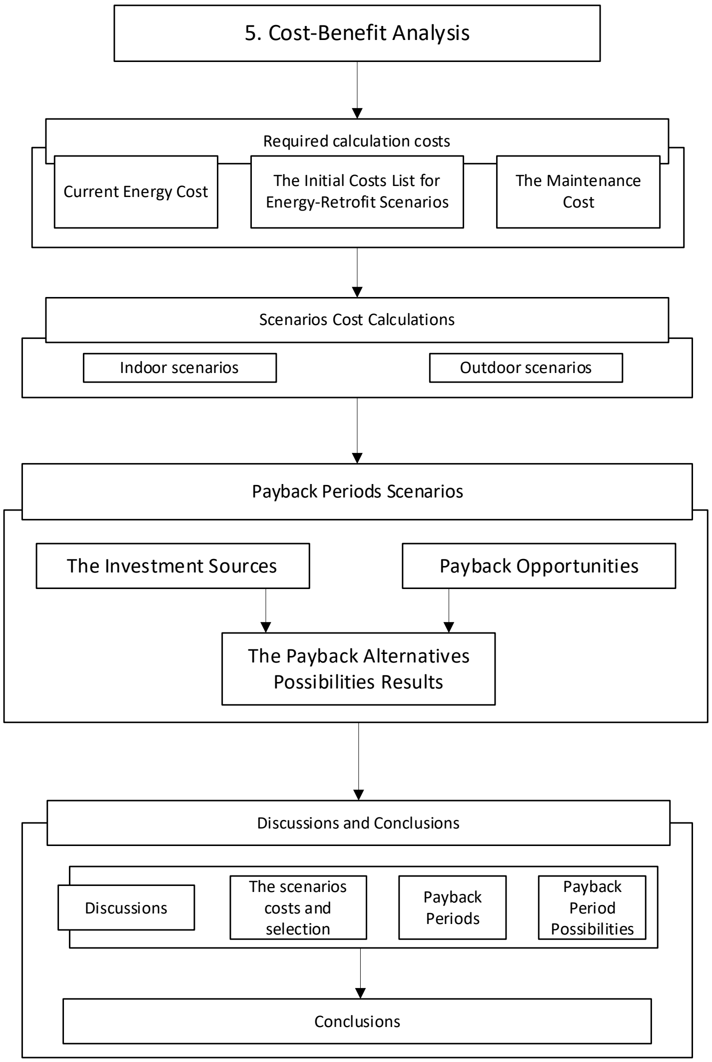

FIG. 5.1 Chapter 5 outline scheme.

The SPT method was used for early evaluation purposes before starting serious analysis. It considers critical components for energy retrofitting applications, such as operational energy costs, initial costs (including local materials, renovation permit fees, and maintenance costs), and available investment options within the Jeddah context [133]. Price data for the study were gathered through direct communication with local companies. Operational energy costs were estimated based on building thermal simulation results, which were then used to evaluate the potential payback time for different investment scenarios. The discussion section provides a comparative analysis of the investment options and identifies the most suitable ones. Figure 5.1 shows the structure of Chapter 5 to help readers understand the chronological steps of this chapter.

5.3 Renovation Costs

This section covers the required costs for each energy-retrofitting scenario and has been divided into three main parts: current energy costs (operational energy costs), initial costs list for energy retrofit scenarios, and maintenance costs.

5.3.1 Current energy cost for electricity

It is vital to calculate the energy operational costs and compare the results to the given scenarios in order to determine the current monthly electricity bill costs. The operational electricity cost calculation utilized two equations:

1- Energy consumption for month 1 X energy tariff= energy cost for month 1

2- ∑ Energy cost for months 1-12 =yearly energy cost

Figure 5.2 illustrates the AAEC values determined in the previous chapter for eight flats in a typical residential building. In addition, the current electricity rates in Saudi Arabia are provided in Table 5.1 [8]. However, the energy tariff rate increases when the monthly energy consumption exceeds 6,000 kWh.

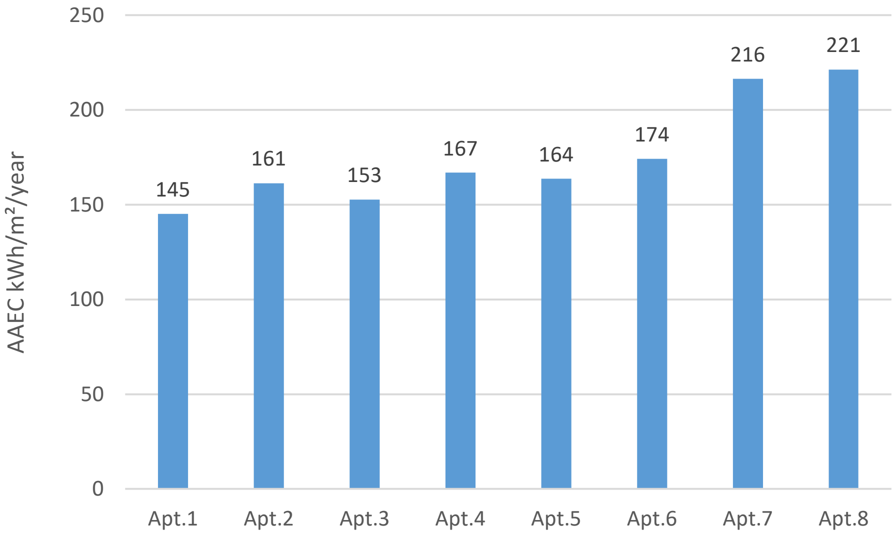

FIG. 5.2 AAEC for 8 apartments in the KSA when the ACH50 is 20.

TABLE 5.1 Current residential energy tariff rates in the KSA.

Consumption Level	Residential
kWh	USD/kWh
≤6000	0.048
>6000	0.08

In Figure 5.3, the monthly energy consumption for each apartment has been calculated to give an overview of the different energy consumption levels of apartments within the same building but in different positions. However, it is necessary to point out that consumers use less energy during the winter months (December, January, and February) than during the rest of the year. The worst month of energy consumption was July for all apartments, as shown in Figure 5.3.

In Figure 5.4, apartments 7 and 8 have a difference in energy consumption costs from May to September compared to the other apartments, reaching up to 555 USD per month. However, three months (December, January, and February) were recorded with minimal costs for all apartments when the AC systems were used less. Table 5.2 illustrates the annual energy costs for each apartment, which vary based on the apartment's position within the building. The upper apartments consume more energy than the lower apartments, which is reflected in the monthly energy costs.

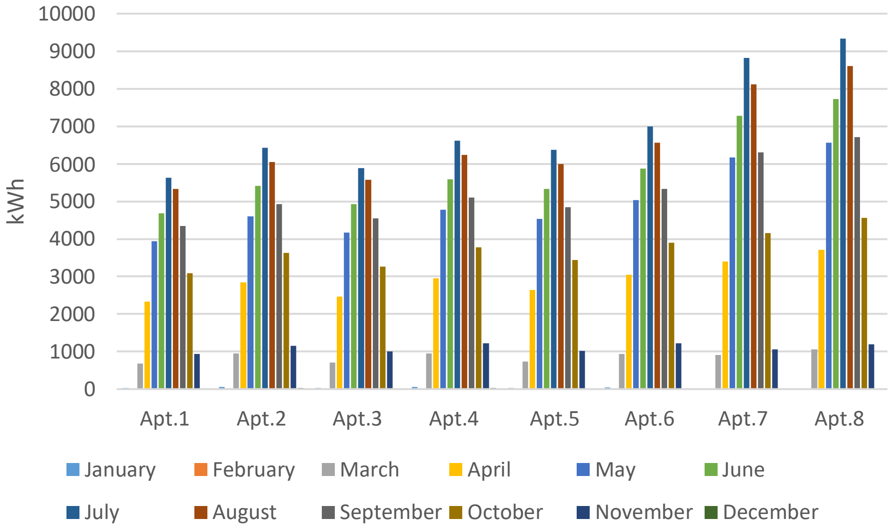

FIG. 5.3 Monthly energy consumption for each apartment.

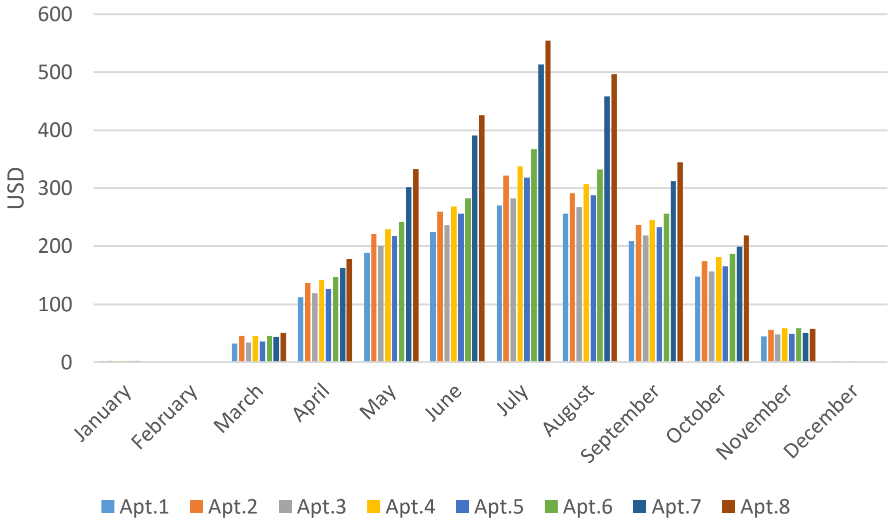

FIG. 5.4 Monthly cost for each apartment.

5.3.2 Cost List for Energy-Retrofit Scenarios

The cost calculation for the energy retrofitting scenario covers firm costs, including issuing a renovation permit and the material and installation costs. Locally, a construction permit is a renovation permit that was initially intended for renovation activities. Short telephone interviews were performed with two firm owners asking participants about renovation permit prices. The renovation permit includes the firm's fees, including the design fees (depending on the project's square meterage and the level of details) and municipality fees. The minimum firm fees were around 400 USD to process the permit request if there was no need for design involvement. However, the municipality fee was about 50 USD cents per square meter [134]. Nevertheless, both firms suggested that a permit was not required if the renovation activities were minimal (no disturbance).

TABLE 5.2 Operational monthly energy cost for each apartment when ACH50 is 20.

	Yearly kWh	Average Monthly Cost (USD)	Average Monthly Cost (SAR)
Apt.1	31004	124	465
Apt.2	36102	146	546
Apt.3	32602	130	489
Apt.4	37315	152	568
Apt.5	34966	141	528
Apt.6	38975	160	600
Apt.7	46230	203	760
Apt.8	49498	222	832

The specific materials that would be necessary for the proposed scenarios were noted, such as cement blocks, insulation, windows, mortar finishing, paint, EIFS, and AC split units. All prices used the USD per m^2 or the USD per unit for AC systems. The prices were collected from different local sources, such as material factories and construction companies. A list of prices illustrates the essential scope and limits the scope list, as shown in Table 5.3.

TABLE 5.3 List prices for necessary energy retrofitting application activity [135]–[138].

List of Prices		USD	SAR
Renovation Permit			
Municipal Fees	Per 1m²	0.5	2
Architecture Firm Fees	Per project	400.0	1500
Insulation			
EPS 25 KG White 5cm	Per 1m²	7.5	28
XPS 35 KG Blue 5cm	Per 1m²	9.3	35
XPS 35 KG Blue 7.5cm	Per 1m²	14.0	52.5
XPS 35 KG Blue 10cm	Per 1m²	18.7	70
XPS 35 KG Blue 15cm	Per 1m²	21.0	78.75
Cement Block			
Materials and Installation	Per 1m²	21.3	80
Windows			
Company (Wintek)	Per 1m²	242.9	911
Company (Creative Windows)	Per 1m²	293.3	1100
Mortar			
Materials and Installation	Per 1m²	9.6	36
Paint			
Paint and Installation	Per 1m²	4.0	15
AC			
Split Unit AC 24 BTU 4 COP	Per unit	853.3	3200
Roof: remove and install ceramic and sand	Per unit	1600.0	6000

5.3.3 Maintenance Costs

The maintenance costs depend on the material lifespan. In this study, the materials differed from one scenario to another. Table 5.3 includes the elements required for an upgrade. The elements were insulation expanded polystyrene insulation (EPS) or extruded polystyrene insulation (XPS), cement blocks, windows, mortar, and AC units. The approximate lifespan of each element is given in Table 5.4. Therefore, maintenance costs have been disregarded, as each material's lifespan would be longer than the payback time of five years (explained in the previous chapter). For instance, if the payback time was more than five years, the paint would need maintenance, which would be an additional cost in the scenario costs.

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TABLE 5.4 Building materials lifespan.

Maintenance		
Object	Life duration (years)	Sources
Paint	5-10	[139]
Stone	60+	[140]
Sealant	10-20	[141]
Windows	25-35	[142]
Insulation		
EPS	35-50	[143]
XPS	Building Lifetime	[143]

5.4 Scenario Cost Calculations

This section presents the total costs of each proposed energy retrofitting scenario for all apartments, categorized into indoor and outdoor scenarios. The indoor scenarios provide various options for individual decision-making, where the positioning of each housing unit may differ. However, the outdoor scenarios have limited possibilities compared to the indoor scenarios, as the decision-making takes place at the building level and involves multiple owners.

Table 5.5 outlines the specific areas of the apartments' façade, floor, and windows, considering two types of floor areas as indicated in the table. The energy-retrofitting costs were evaluated based on the location of the apartments and the level of intervention required, considering indoor or outdoor scenarios. The costs were categorized into five groups based on the floor area size and level of intervention. Table 5.6 presents the cost calculation for apartments 1, 3, and 5. Tables 5.8, 5.9, and 5.10 provide the corresponding data for the remaining apartments (2, 4, 6, 7, and 8). To facilitate the analytical process, the study focused on four representative apartments, namely apartment 1 (representing apartments 2, 3, and 5), apartment 2 (representing apartments 2, 4, and 6), apartment 7, and apartment 8.

TABLE 5.5 Apartment area specification from the previous chapter.

Apartments	Façade Area (m²)	Window Area (m²)	Floor Area (m²)
1,3,5,7	130	11.7	215
2,4,6,8	133	12	225

TABLE 5.6 Total cost calculations for apartments 1, 3, and 5.

Apartments 1,3,5	Scen. 1	Scen. 2	Scen. 3	Scen. 4	Scen. 5	Scen. 6	Scen. 7	Scen. 8	Scen. 9	Scen. 10
Initial Cost										
Renovation Permit cost	1523	1927	1927	1927	1927	1951	1951	1951	1951	1951
Insulation Cost	0	3629	4536	6804	9072	9072	9072	9072	9072	9072
Window Cost	12855	0	0	0	0	10646	12855	12855	12855	12855
AC Cost (8 Units)	0	0	0	0	0	0	0	0	0	25600
Roof Insulation	0	0	0	0	0	0	0	0	0	0
Finishing Mortar	0	4666	4666	4666	4666	4666	4666	4666	4666	4666
Paint	0	1944	1944	1944	1944	1944	1944	1944	1944	1944
Block Wall 10cm	0	10368	0	0	0	0	0	0	0	0
Total Cost SAR +15% VAT	**16535**	**25914**	**15034**	**17642**	**20251**	**32520**	**35060**	**35060**	**35060**	**64500**
Total Cost USD	**4409**	**6910**	**4009**	**4705**	**5400**	**8672**	**9349**	**9349**	**9349**	**17200**

TABLE 5.7 Cost calculation for outdoor scenarios.

All Apartments	Scen. 1	Scen. 2	Scen. 3	Scen. 4	Scen. 5	Scen. 6	Scen. 7
Initial Cost							
Renovation Permit Cost	4222	4222	4459	4459	5334	5334	5334
Insulation Cost	224565	238175	238175	238175	238175	238175	238175
Window Cost	0	0	86541	104496	104496	104496	104496
AC Cost (8 Units)X (8APT)	0	0	0	0	0	0	204800
Roof Insulation	0	0	0	0	36616	40443	36616
Finishing Mortar	0	0	0	0	0	0	0
Paint	20415	20415	20415	20415	20415	20415	20415
Block Wall 5cm	0	0	0	0	0	0	0
Total Cost SAR for 8 APT. +15% Tax	286583	302234	402030	422677	465792	470193	701312
Total Cost USD for 8 APT.	**76422**	**80596**	**107208**	**112714**	**124211**	**125385**	**187016**
Total Cost SAR per APT.	**35823**	**37779**	**50254**	**52835**	**58224**	**58774**	**87664**
Total Cost USD per APT.	**9553**	**10074**	**13401**	**14089**	**15526**	**15673**	**23377**

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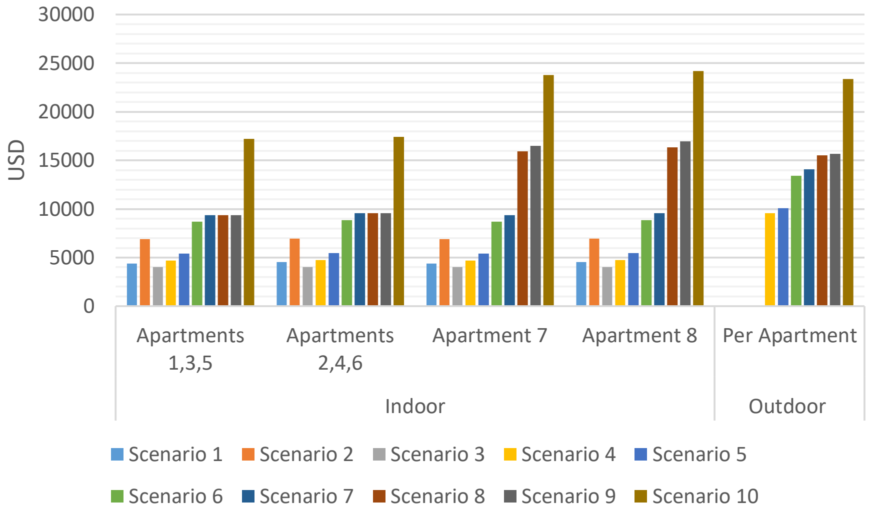

FIG. 5.5 Cost calculation for proposed scenarios for all apartments (indoor and outdoor).

Table 5.6 presents a variation in the cost calculation for scenarios implemented in apartments 1, 3, and 5. Scenarios 7-9 have similar total costs, with roof interventions only applicable for apartments 7 and 8. The total cost of energy retrofitting for outdoor scenarios is distributed identically across all apartments, as shown in Table 5.7, as the decision-making process is at the building level.

Figure 5.5 compares the proposed total cost of various scenarios and shows the differences between scenarios and apartments. Scenarios 8-10 have the highest costs, especially for apartments 7 and 8. However, the next chapter will demonstrate the payback possibilities to determine the economic feasibility of these interventions for the proposed scenarios.

TABLE 5.8 Total cost calculations for apartments 2, 4 and 6.

Apartments 2,4,6	Scen. 1	Scen. 2	Scen. 3	Scen. 4	Scen. 5	Scen. 6	Scen. 7	Scen. 8	Scen. 9	Scen. 10
Initial Cost										
Renovation Permit Cost	1524	1767	1767	1767	1767	1791	1791	1791	1791	1791
Insulation Cost	0	3735	4669	7004	9339	9339	9339	9339	9339	9339
Window Cost	13269	0	0	0	0	10989	13269	13269	13269	13269
AC Cost (8 Units)	0	0	0	0	0	0	0	0	0	25600
Roof Insulation	0	0	0	0	0	0	0	0	0	0
Finishing Mortar	0	4803	4803	4803	4803	4803	4803	4803	4803	4803
Paint	0	1944	1944	1944	1944	1944	1944	1944	1944	1944
Block Wall 10cm	0	10368	0	0	0	0	0	0	0	0
Total Cost SAR +15% VAT	17012	26010	15160	17845	20530	33196	35818	35818	35818	65258
Total Cost USD	4537	6936	4043	4759	5475	8852	9551	9551	9551	17402

TABLE 5.9 Total cost calculations for apartment 7.

Apartment 7	Scen. 1	Scen. 2	Scen. 3	Scen. 4	Scen. 5	Scen. 6	Scen. 7	Scen. 8	Scen. 9	Scen. 10
Initial Cost										
Renovation Permit Cost	1523	1927	1927	1927	1927	1951	1951	2378	2378	2378
Insulation Cost	0	3629	4536	6804	9072	9072	9072	9072	9072	9072
Window Cost	12855	0	0	0	0	10646	12855	12855	12855	12855
AC Cost (8 Units)	0	0	0	0	0	0	0	0	0	25600
Roof Insulation	0	0	0	0	0	0	0	20956	22825	20956
Finishing Mortar	0	4666	4666	4666	4666	4666	4666	4666	4666	4666
Paint	0	1944	1944	1944	1944	1944	1944	1944	1944	1944
Block Wall 10cm	0	10368	0	0	0	0	0	0	0	0
Total Cost SAR +15% VAT	16535	25914	15034	17642	20251	32520	35060	59651	61800	89091
Total Cost USD	4409	6910	4009	4705	5400	8672	9349	15907	16480	23757

TABLE 5.10 Total cost calculations for apartment 8.

Apartment 8	Scen. 1	Scen. 2	Scen. 3	Scen. 4	Scen. 5	Scen. 6	Scen. 7	Scen. 8	Scen. 9	Scen. 10
Initial Cost										
Renovation Permit Cost	1524	1767	1767	1767	1767	1791	1791	2238	2238	2238
Insulation Cost	0	3735	4669	7004	9339	9339	9339	9339	9339	9339
Window Cost	13269	0	0	0	0	10989	13269	13269	13269	13269
AC Cost (8 Units)	0	0	0	0	0	0	0	0	0	25600
Roof Insulation	0	0	0	0	0	0	0	21661	23618	21661
Finishing Mortar	0	4803	4803	4803	4803	4803	4803	4803	4803	4803
Paint	0	1944	1944	1944	1944	1944	1944	1944	1944	1944
Block Wall 10cm	0	10368	0	0	0	0	0	0	0	0
Total Cost SAR +15% VAT	17012	26010	15160	17845	20530	33196	35818	61242	63493	90682
Total Cost USD	4537	6936	4043	4759	5475	8852	9551	16331	16932	24182

5.5 Scenario Payback Periods

The payback period calculations comprise two aspects: investment cost and payback measures. The possible payback options are set out below.

5.5.1 Investment cost

The investment cost section has been divided into two primary categories: investments with profit (with or without an added interest rate) and non-profit investments (with zero interest). Using updated pricing information, the objective was to present generalized investment options that could be further refined in future calculations to meet specific design criteria.

A Investments with profit

In the context of the KSA, funding sources for investments with profit are primarily banks and developers' companies. The latter refers to private investors who aim to gain revenue from energy retrofitting. However, banks cater to individual decision-making options and offer various types of real estate finance. Differences among bank loans are mainly dependent on the interest rate and the minimum household salary requirement, which vary across different banks.

Due to the dynamic nature of bank interest rates, two rates were selected in this study in order to present realistic payback alternatives. Table 5.11 provides a comparison of interest rates offered by different banks, revealing that Riyad Bank and Alawal Bank offer the lowest interest rates (1.85%), while Saudi Fransi Bank and Al-Jazira Bank offer the highest interest rates (4.78%-5.44%) [144]. The analysis in this study concentrates on the extremes of this range, namely the lowest rate (1.85%) and the highest rate (5.44%).

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TABLE 5.11 Bank interest rate options and minimum salaries in 2020 [144].

Source	Interest rate	Down payment	Min. Salary in USD	Type
SAB Bank	3.59%	15%	1333	Real State
Riyad Bank	1.85%	15%	1333	Real State
Al-Jazira Bank	4.78%	15%	1333	Real State Housing
ANB Bank	3.99%	30%	533	Real State Housing
Alawal Bank	1.85%	15%	2667	Real State
Saudi Fransi Bank	5.44%	30%	1600	Real State
Ahli Bank	3.73%	15%	1333	Real State
Al-Rajhi bank	2.23%	30%	1333	Real State

Furthermore, the loan options offered by the banks had varying durations ranging from 5 to 10 years and distinct interest rates (profit) for investors. The investigation emphasized a ten-year term, including the five-year option. The ten-year term was selected since it generates over twice the profit compared to the five-year option, as depicted in Figure 5.6, and must be factored into the payback computations. The initial costs of each scenario after incorporating the interest rates (1.85% and 5.44%) for a ten-year loan are presented in Figures 5.7 and 5.8.

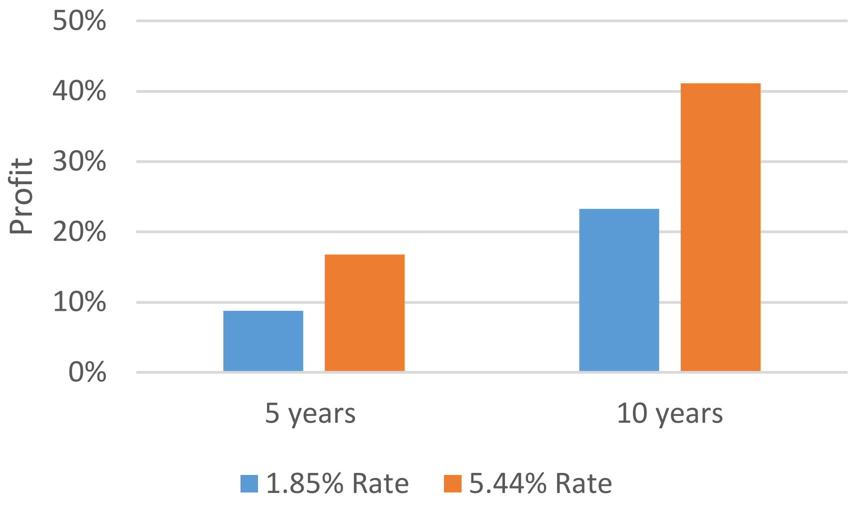

FIG. 5.6 Profit comparison of different interest rates.

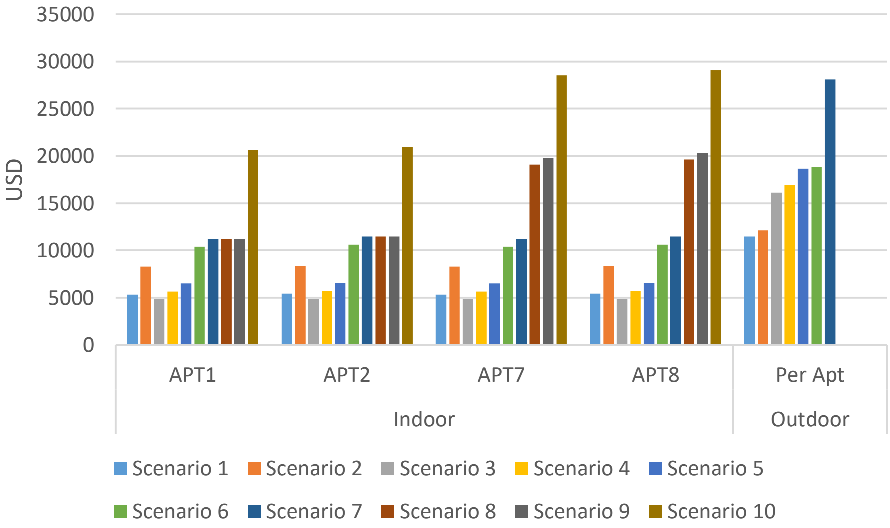

FIG. 5.7 Total cost with 1.85% interest rate.

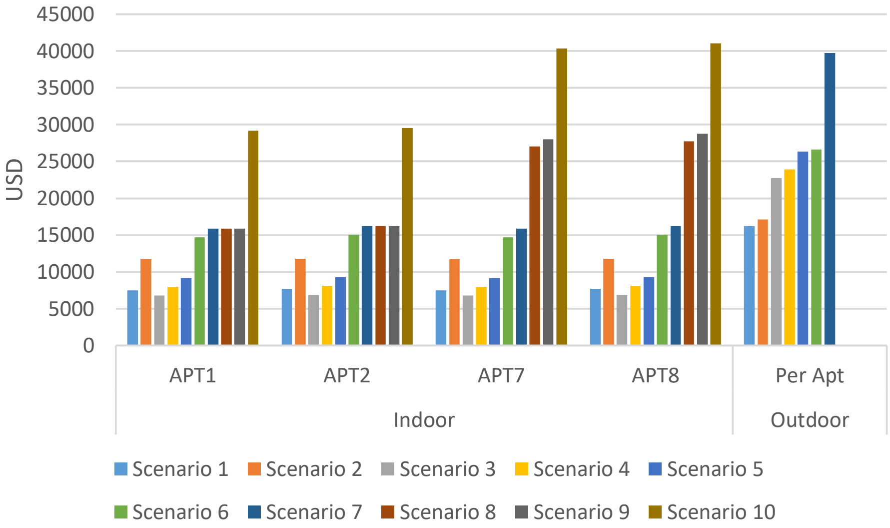

FIG. 5.8 Total cost with 5.44% interest rate.

B Non-profit investments (i.e., zero interest)

In the KSA, non-profit investments are primarily represented by individual savings or government-sponsored programs with zero interest rates. Individual savings typically involve sources such as personal savings, loans from friends or relatives, and other similar sources with no interest. However, government-sponsored programs are funding schemes provided by a government organization with a zero interest rate.

In the KSA, two funding programs exist for building improvements/retrofitting: the SDB and the Sakani (Housing) program. The SDB program allows citizens to borrow a maximum of 16,000 USD and repay it within five years, subject to a maximum monthly income of 3,334 USD [94]. However, the SDB program is active but limited due to the available funds of the SDB organization. The Sakani program allows a maximum of 13,333 USD for apartments [40]. The Sakani program is inactive and has been put on hold due to ongoing housing construction programs.

5.5.2 Payback Measures

The payback calculation in this study utilized energy savings in USD as the primary metric. However, it is crucial to justify the various variables that inform the payback calculation method. The SPT method [133] was adopted, and the main variables considered in the payback calculation were interest rates, increasing electricity tariffs, and oil savings. These variables were included in the payback calculation, which initially only accounted for energy savings, to provide a more comprehensive understanding of the total payback period.

The interest rates offered by banks were previously discussed in Section 5.5.1, while the payback time will be elaborated further in Subsection 5.5.3. It is worth noting that increasing the electricity tariff rates can result in shorter payback periods. To explore this further, two Scenarios were considered for energy tariff increases: a 20% increase (Table 5.12) and a 50% increase (Table 5.13).

In addition, the potential for oil savings is a crucial factor that can significantly reduce the payback period. Therefore, it is necessary to perform a brief calculation of the housing unit to incorporate this factor into the payback calculation.

TABLE 5.12 Increasing electricity tariff by 20%.

Consumption Level	Residential
kWh	USD/kWh
≤6000	0.058
>6000	0.096

TABLE 5.13 Increasing electricity tariff by 50%.

Consumption Level	Residential
kWh	USD/kWh
≤6000	0.072
>6000	0.120

A Oil savings assumption per housing unit

The aim of this study was to analyze the residential sector in Jeddah, located in the Makkah province of Saudi Arabia. According to estimates, the province houses 970,061 apartment units, assuming that Jeddah accounts for 60% or approximately 582,037 units [51]. This figure roughly represents slightly above 10% of the overall number of apartments in the KSA, which stands at 5,466,910 apartments. Therefore, the study further revealed that Jeddah's share of the total daily oil consumption in the residential sector is approximately 10%, equivalent to 67,818 barrels per day out of the total country consumption of 637,000 (50% of 1.3 million) barrels per day [2]. This finding is significant given that the KSA's average daily oil consumption between 2009 and 2018 was 7.1 million barrels per day [145]. Table 5.14 outlines various options for energy savings results for exporting oil (selling option) and generating electricity locally (current cost of energy consumption). It shows that the oil cost calculation was based on the average oil price of 78.59 USD per barrel during the same period (2009-2018) [145].

TABLE 5.14 Comparison assumption between oil consumption (generating electricity) vs. export (selling opportunity) for Jeddah apartments in 1, 10, 20, and 30 years.

Oil Options	USD	Million	Billion	Billion	Billion	Billion
	price	1 day	1 year	10 years	20 years	30 years
Export (Selling)	78.59	5.3	1.9	19.5	38.9	58.4
Generating Electricity	5	0.3	0.1	1.2	2.5	3.7

TABLE 5.15 Oil consumption vs. oil selling for a housing apartment in Jeddah.

Oil Options	USD	1 day	1 month	1 year
Export	78.59	9.2	274.7	3342.4
Generating Electricity	5	0.6	17.5	212.6

Moreover, Table 5.15 illustrates the calculation of the cost of oil per housing unit, estimated to be an average of 0.6 USD apartment/day. If that oil is sold for 9.2 USD, it could generate significant income for the KSA economy. The income calculation is based on dividing the total barrels of oil consumed in Jeddah by the total number of apartments, multiplied by the oil barrel cost (generating electricity or selling). Therefore, the total income per housing unit per year could be estimated by multiplying the percentage of energy savings by the yearly selling price (3342.4 USD), as presented in Table 5.15.

Ultimately, these findings highlight the potential for energy retrofitting to shorten payback periods when including the oil selling opportunity, which is a crucial factor for investors. Thus, oil-selling payback measures could increase the possibilities for energy retrofitting applications.

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5.5.3 Payback Alternative Possibilities

Based on the aforementioned variables and the possible opportunities, 8 alternatives for payback options were investigated, as shown in Table 5.16. The payback alternative design goal was to reach lower payback periods for the ERA scenario, where five years was set as a maximum, as this could align with governmental financial supporting programs. In addition, the calculation included the following equation: SPT=I/P (SPT= simple payback time, I= investment, P= annual savings), and the alternatives are described in more detail below.

TABLE 5.16 Eight payback alternatives.

Payback Alternatives	Investment Model	Payback Measures
1	Zero Interest[1]	ES
2	Interest Rate[2] (1.85%)	ES
3	Interest Rate[2] (5.44%)	ES
4	Zero Interest[1]	ES + 20% ETI
5	Zero Interest[1]	ES + 50% ETI
6	Zero Interest[1]	ES + OS
7	Zero Interest[1]	ES + 20% ETI + OS
8	Zero Interest[1]	ES + 50% ETI + OS

**Zero Interest (Individual /Governmental) *Interest Rate (Bank or Private Developer) *Energy Savings (ES) *Electricity Tariff Increase (ETI) *Oil Selling (OS)*

A First Alternative

The first alternative was to consider only the energy savings with zero-interest investment where the calculation equation was as follows:

Payback period = total investment (zero interest) ÷ energy savings

Earlier in the chapter, Figure 5.5 illustrated the total cost for each scenario, yet the yearly energy savings percentage ranged between just below 20% up to 65%, as shown in Figure 5.9. In addition, regarding energy savings, the apartment's position plays a significant role in selecting which scenario is more effective in terms of the energy savings percentage than the others. For instance, Scenarios 8-10 (indoor) and 5-7 (outdoor) were more effective for apartments 7 and 8 compared to the other scenarios. Figure 5.10 shows the yearly savings in USD converted from the energy savings consumption, which has been included in the payback equation.
Figure 5.11 illustrates the first alternative in respect of payback periods, where the best indoor scenarios were 3-5 as they fall between 5 and 7 years of payback, while the rest involved more than 7 years of payback. However, the outdoor scenarios exceeded 10 years of payback, which resulted in additional costs such as maintenance costs (repainting). However, the payback years for the indoor scenarios started from just above 5 years up to just above 18 years, while outdoor scenarios started from around 10 years up to just below 25 years of payback time. The first alternative could be applicable for individual savings investment, but almost all scenarios could not reach the 5 year payback target

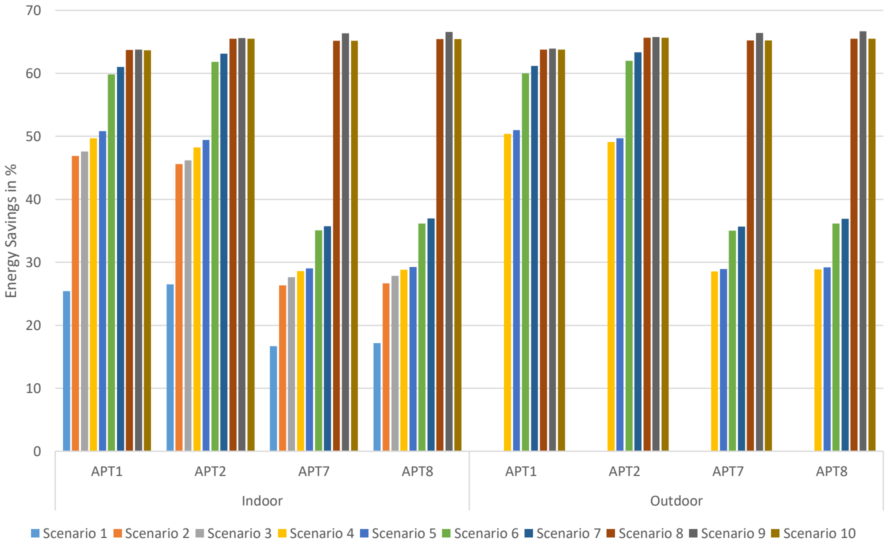

FIG. 5.9 Yearly energy savings percentages.

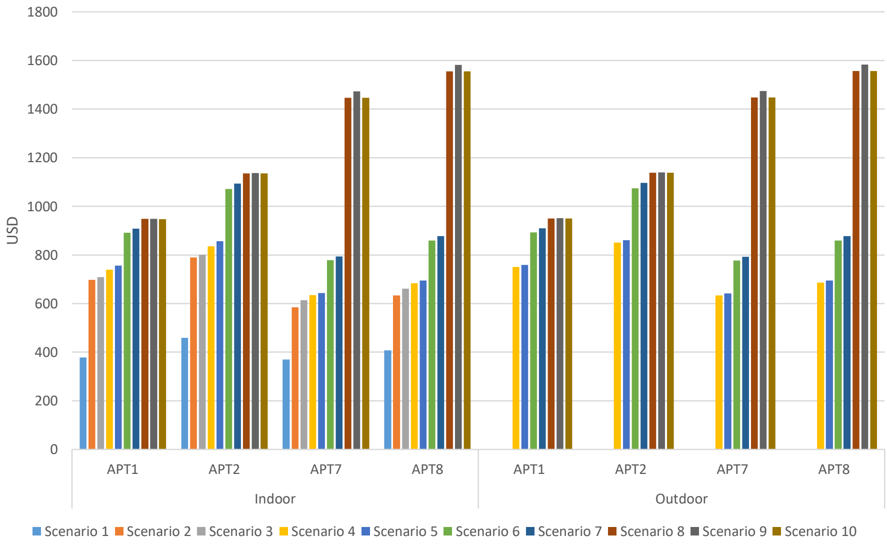

FIG. 5.10 Yearly USD savings per apartment per scenario.

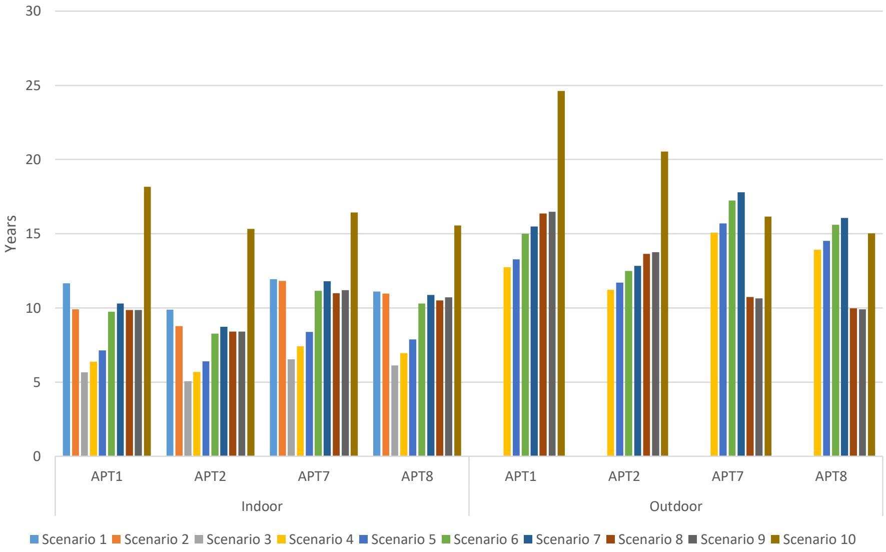

FIG. 5.11 Payback periods for alternative 1.

B Second and Third Alternatives

The central concept for the second and third alternatives was to illustrate the impact of adding the interest rate to the payback periods. The two alternatives considered the same energy savings percentage but with different interest rates added to the investment, where the calculation equation was as follows:

Payback period = total investment (1.85% or 5.44% interest) ÷ energy savings

The study quantified the effect of 5- and 10-year loans as a profit for the investor (banks/developers) and additional payback years for the owners, where Figure 5.6 showed the percentage difference as the gain is almost double. However, the two alternatives (second and third) added additional costs to the investments, adding more years to the payback periods, as shown in Figure 5.12 and Figure 5.13.

However, the alternatives involving payback periods with interest rates (1.85% and 5.44%) for the indoor scenarios started from just above 6 and 8.5 years up to 22 and 30 years, respectively. The payback periods for the outdoor scenarios started from around 12 to 17 years up to just below 30 and 42 years of payback periods, respectively. The second and third alternatives are not recommended, as they add an enormous number of years to the payback periods unless the lower interest rate is applied by selecting the shortest periods. However, banks and development companies would find these two alternatives beneficial.

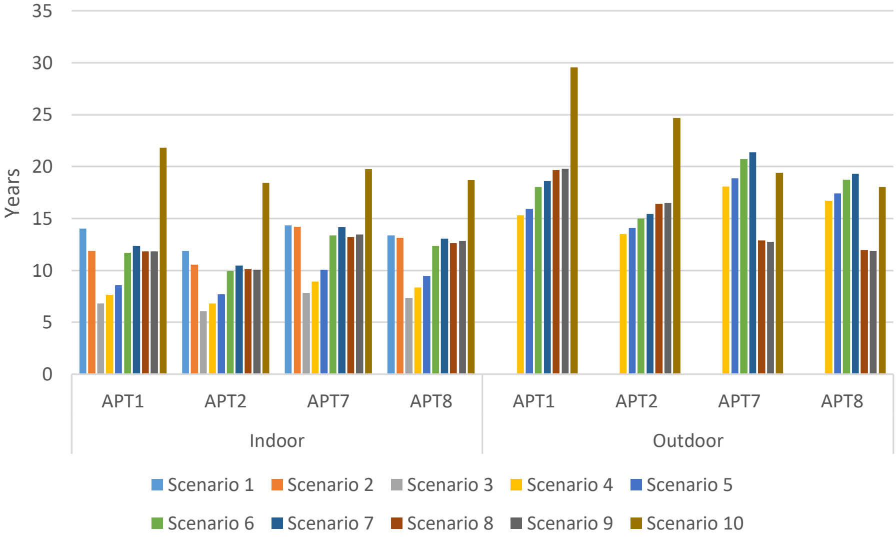

FIG. 5.12 Payback periods for alternative 2 (1.85% interest rate).

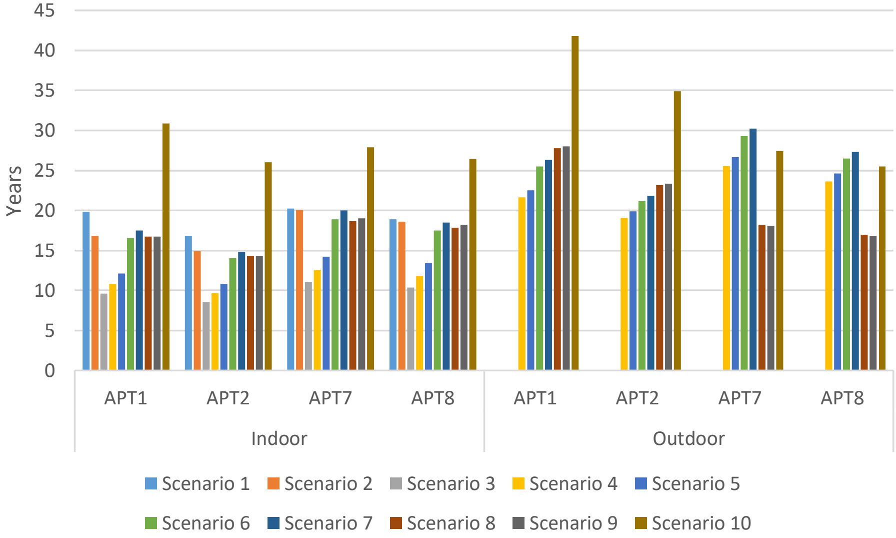

FIG. 5.13 Payback periods for alternative 3 (5.44% interest rate).

C Fourth and Fifth Alternatives

The significant factor for alternatives 4 and 5 was adding an annual savings measure (the electricity tariff increase (ETI)) to lower the payback periods, which represents an additional cost to the monthly electricity bills. The two alternatives consider adding an ETI (20% or 50%) to the energy savings percentage but with a zero interest-rate of investment, where the calculation equation was as follows:

Payback period= total investment (zero interest) ÷
(energy savings + ETI (20% or 50%)).

Figures 5.14 and 5.15 present alternatives 4 and 5, which consider adding a 20% and 50% ETI to the annual savings. When adding a 20% ETI, Scenarios 3-5 of the indoor type reached less than 5 years, while most of the other scenarios of the indoor and outdoor types reached more than 6 years. However, the payback periods were less than alternatives 1, 2, and 3. However, adding a 50% ETI was more significant in payback periods compared to alternative 4, in which most indoor scenarios fall below 5 years, and most outdoor scenarios fall below 8 years. Alternatives 4 and 5 are applicable for governmental programs as adding the ETI could be used as a condition for the governmental financial support of ERA total cost investment.

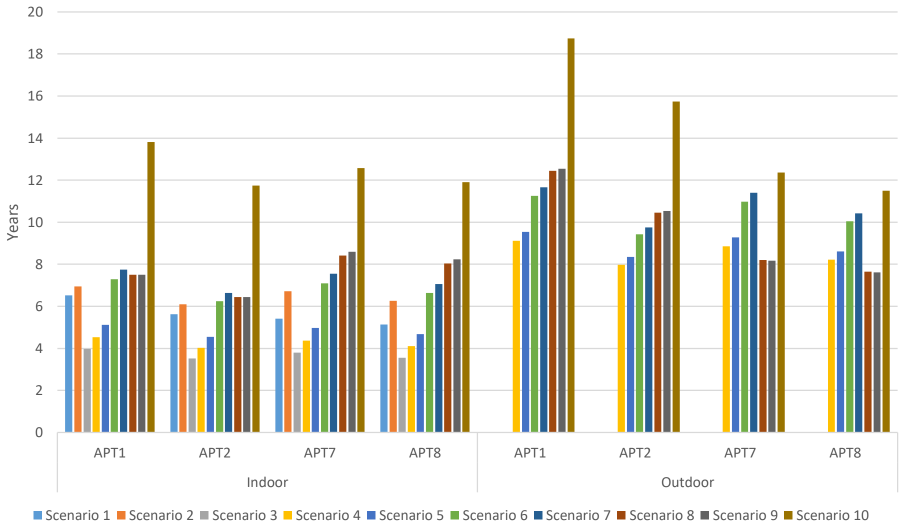

FIG. 5.14 Payback periods for alternative 4 (add 20% ETI).

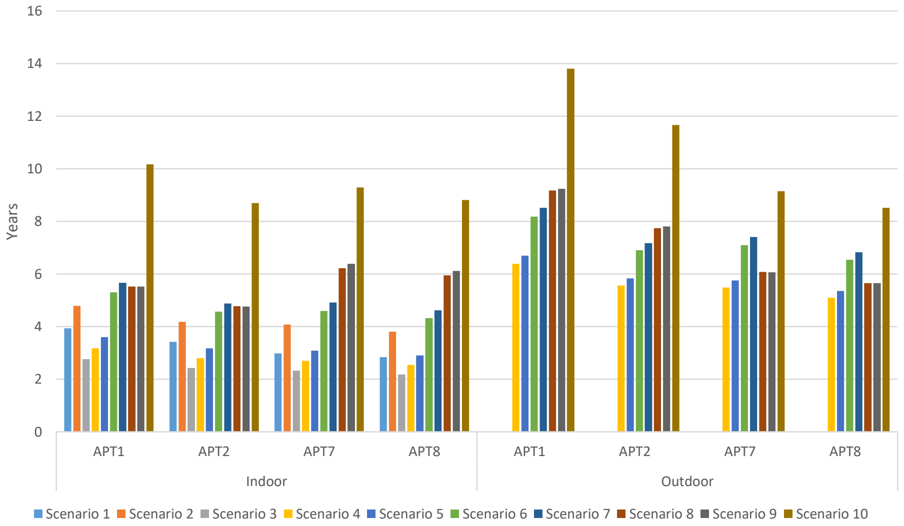

FIG. 5.15 Payback periods for alternative 5 (add 50% ETI).

D Sixth Alternative

The central concept for alternative 6 was to add the assumption of oil savings to the annual savings, which would reduce payback periods. Alternative 6 considered adding oil selling (OS) to the annual energy savings percentage with a zero interest-rate of investment, where the calculation equation was as follows:

Payback period= total investment (zero interest)÷ (energy Savings+ OS)

Figure 5.16 shows the payback periods of alternative 6, where most of the scenarios are below 5 years while a few fall below 8 years. Furthermore, the payback periods for the indoor scenarios start from just above 1.5 years and reach just above 6.5 years, while the outdoor scenarios start from below 4 years and reach just above 7.5 years of payback time.

Hence, most scenarios reach below 5 years, making alternative 6 the most practical alternative with limitations to some scenarios greater than 5 years. Alternative 6 is applicable for governmental financial support programs with a condition of the governmental financial budget covering the total cost and payback support for the ERA.

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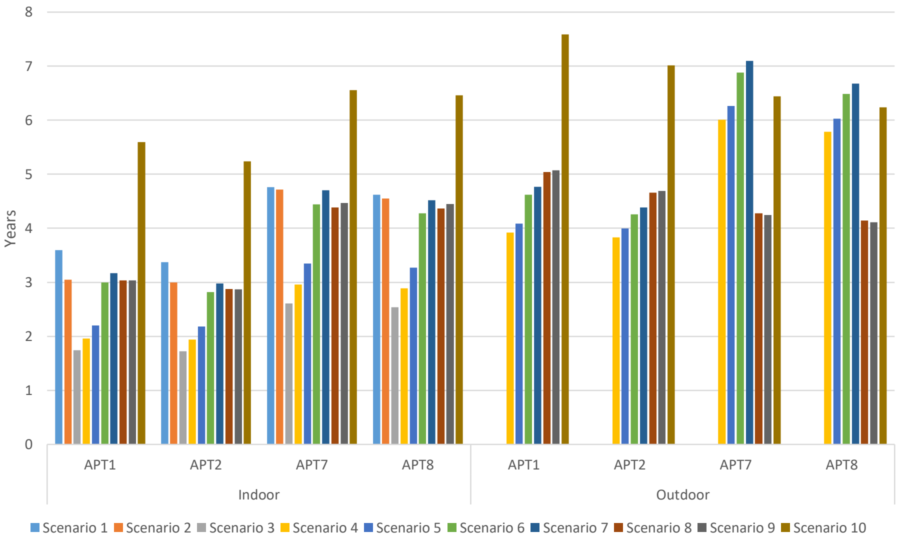

FIG. 5.16 Payback periods for alternative 6 (add OS).

E Seventh and Eighth Alternatives

The central concept of alternatives 7 and 8 was to increase the reduction possibilities of the payback years of the proposed scenarios by adding an ETI saving measure. The alternatives here were considering adding the oil selling (OS) and the ETI (20%, 50%) to the energy savings measure with zero-interest investment, for which the calculation equation was as follows:

Payback period= total investment (zero interest) ÷
(energy savings + OS +ETI (20% or 50%))

Figures 5.17 and 5.18 show the payback periods of alternatives 7 and 8, where the payback years of indoor scenarios of alternatives 7 and 8 started from just above 1.5 and 1 year up to just below 6 and 4.5 years, respectively. In addition, the outdoor scenarios started from just above 3.5 and just below 3 years, up to just below 7 and just above 6 years of payback, respectively. Alternative 8 revealed that almost all scenarios (indoor and outdoor) fall below 5-year payback periods, which was the main aim of the cost–benefit analysis. However, alternatives 7 and 8 are applicable for governmental financial support programs but with increasing monthly bills to support the payback analysis.

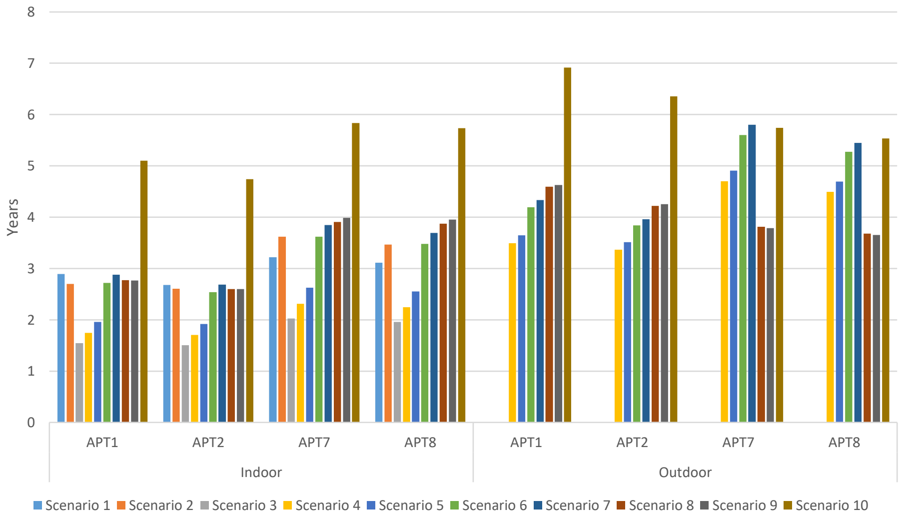

FIG. 5.17 Payback periods for alternative 7 (add OS + add 20% ETI).

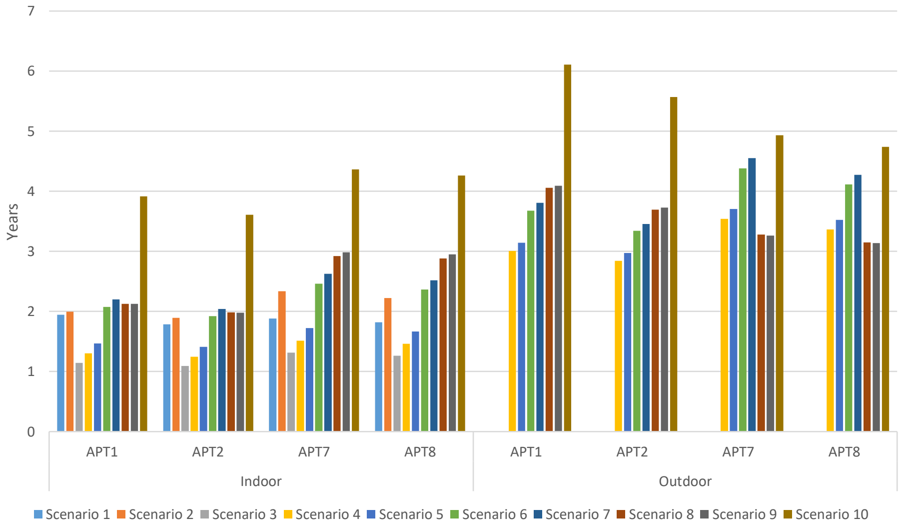

FIG. 5.18 Payback periods for alternative 8 (add OS + add 50% ETI).

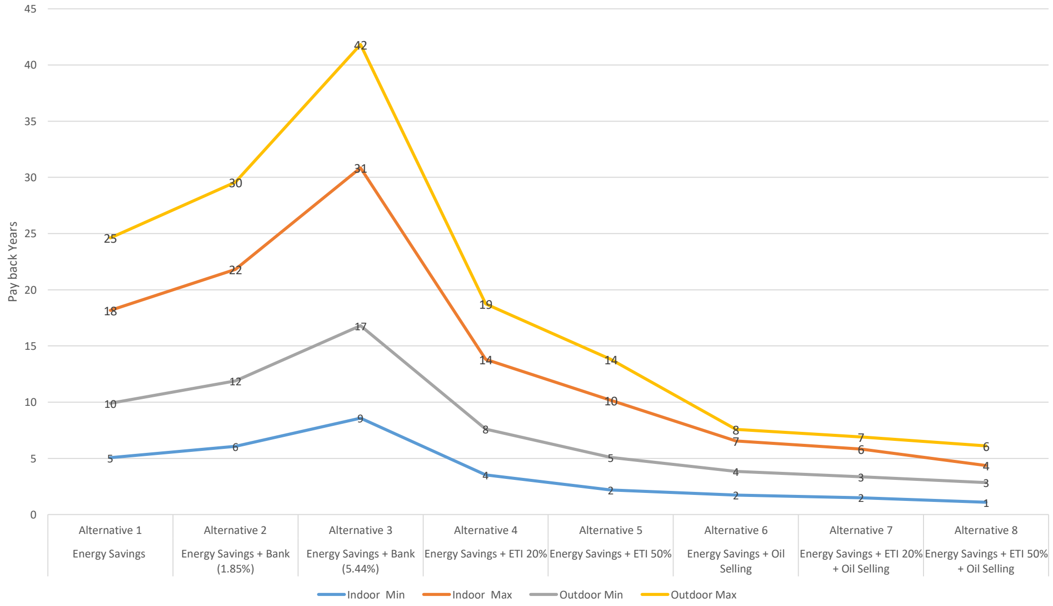

FIG. 5.19 Comparison of eight ERA payback scenarios.

This chapter has given an overview of possible payback alternatives for energy retrofitting applications, including different investment models with different payback measures. Hence, Figure 5.19 shows a comparison between eight ERA payback alternatives. Figure 5.19 shows the minimum and maximum payback years of indoor and outdoor scenarios, which could support ERAs for residential buildings in the KSA context. Each alternative has pros and cons, which will be addressed further in the discussion section. Hence, there are many promising payback alternatives by which to implement ERAs for residential buildings in Jeddah.

Regarding payback periods, Figure 5.19 shows that alternatives 6, 7, and 8 are superior to the other options because they generally result in shorter periods. However, alternatives 2 and 3 add excessive years relative to alternative 1. In order to achieve a payback period of 5 years, the first alternative was used as a baseline for all others, and alternatives 2 and 3 were disregarded.

Alternatives 4 and 5 have shorter payback periods than alternative 1, but increase monthly energy bills for households. In the current economic climate, it is challenging to incur additional monthly expenses, but there may be an opportunity to design government assistance for specific household needs.

Adding the oil-selling assumption to the annual savings resulted in a significant decrease in payback periods for alternative 6. The primary challenge of alternative 6 is the required government budget. However, ERAs could become more feasible if the government's return income was calculated for an extensive application. In addition, alternatives 7 and 8 aimed to meet the 5-year benchmark, which was successfully met in most scenarios.

5.6 Discussion

This section discusses the cost challenges in terms of scenario selection, as well as costs, payback period variables, and possibilities.

Initially, the main challenge for cost calculations is determining the actual cost for materials and labor. However, after the COVID-19 pandemic, many material companies recently activated their websites and posted prices. Therefore, reliable prices were found that local companies verified. In addition, the renovation costs were justified (Section 5.3) by providing a baseline for costs and constructing all of the following calculations in relation to that baseline.

In addition, the number of apartments was limited by selecting representative apartments to achieve tangible results. In contrast, the analysis was extended to all the scenarios presented in Chapter 4 to obtain the most effective alternatives. The cost calculations for each case require detailed information regarding energy consumption and prices to achieve reliable results.

It was found that payback alternatives depend on two main variables: investment options and payback measures. The chapter discussed two types of investments (zero interest rate and with interest rate). The payback periods increased when adding interest costs, but only if the same payback measure was used. The analysis presented around a 20% to 40% increase in payback years when only adding 1.85% and 5.4% interest rates, respectively. Therefore, worldwide, it is challenging to execute ERAs for residential buildings when interest rates are involved.

Conversely, the alternatives of increasing the electricity tariffs by 20% and 50% achieved lower payback years of around 25% and 45% compared to alternative 1. However, in the KSA context, such increases in electricity tariffs are insufficient as the electricity tariffs have already doubled four times, and living expenses have increased lately.

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Furthermore, the most crucial factor in cost-effectiveness plans is the oil savings, which depend on the percentage of energy consumption savings as the KSA relies on burning oil to produce electricity. Alternative 6, which includes oil-selling calculations, achieved lower payback years of around 70% compared to alternative 1. Nevertheless, the state must assign a budget for executing such an alternative.

Hence, the alternatives were explicitly designed for the context of Jeddah, including calculating the required cost and suggesting various payback measures. The analysis yielded significant findings regarding cost-effective and advantageous payback alternatives for the intended group (households, government, and banks). However, the ERA requires additional investigation on a larger scale (city-level) to make the appropriate decisions.

5.7 Conclusions

In this chapter, the economic viability of the scenarios proposed in the preceding chapter was examined, which was one of the ERA's challenges. The payback period was used as a critical indicator for the proposed ERA scenarios for mid-rise residential buildings in Jeddah. The investment cost and return on investment were two of the most critical variables. The study examined the effects of the many variables on the payback periods for various payback alternatives.

Costs were calculated for all possible scenarios involving four representative apartments, including current energy, retrofitting intervention, and maintenance costs. In addition, the chapter elaborated on two specific investments (profit and non-profit) and three payback measures (energy savings, ETI, and oil selling). As a result, eight payback alternatives were illustrated and compared in terms of payback periods to highlight the Jeddah-appropriate scenarios.

In terms of return on investment, the presented findings suggest that many alternative scenarios are satisfactory. In general, adding interest rates to investment costs harmed the payback periods. In contrast, adding ETI to the annual savings reduced the payback periods while increasing users' monthly bills. Adding oil sales revenue to annual savings significantly reduced payback periods but required a substantial government budget. Economically, all parties (households, government, market, and building energy) would benefit from energy retrofitting applications, but in different ways, as detailed in the following chapter, which predicts the effects of ERAs on mid-rise residential buildings in Jeddah.

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6 Consequences of Energy Retrofitting Applications on Residential Buildings (mid-rise) in the KSA

Jeddah as a Case Study

Chapters 4 and 5 presented potential ERA results using energy simulation and cost–benefit analysis for different housing units in Jeddah. Both chapters provided scientific evidence of the possibility of applying ER scenarios to a housing unit in Jeddah city. However, the decision-making in relation to ERAs needs further investigation at the city-level, which requires a different level of effectiveness. Therefore, this chapter gives an overview of the consequences of ERAs on residential buildings for three groups (stakeholders, state, market and community), which should help decision-makers predict the future consequences of ERAs. The chapter illustrates three main aspects of ERAs: the challenges, the beneficial parties, and the decision-making approach. Calculations are provided for different parameters on a city-wide scale to determine the consequences of ERAs on residential buildings in Jeddah city.

Section 6.1 introduces the importance of ERAs and the necessity of understanding the consequences of ERAs within the KSA context. Section 6.2 presents the four main ERA challenges within the Jeddah context. Section 6.3 specifies the ERA beneficiaries (state, market, and community). Section 6.4 describes the ERA decision-making approach. Section 6.5 provides calculations for 42 different scenarios for different parameters on a city-wide scale. The selected scenarios are defined in the same section and the results are presented in four groups to ease the comparison. Section 6.6 defines three study models based on specific cases with three different conditions. Section 6.7 discusses the ERA consequences for the state, the market, and the community. Finally, Section 6.8 presents the conclusions.

6.1 Introduction

The essential step in any energy retrofitting project is understanding the impact of the proposed interventions to enable informed decision-making for all energy-upgrade representatives, such as the Ministry of Municipal and Rural Affairs (MOMRA), SEEC, SBC, and homeowners. The previous chapters presented the potential of energy retrofitting applications (ERAs) for mid-rise residential buildings, demonstrating significant energy savings and cost-effectiveness. Given the Saudi government's aim to achieve net-zero emissions by 2060, it is imperative to examine the impact of ERAs on a city-wide scale and identify the needs of different stakeholders [41], [72]. The aim of this study is to provide decision-makers with an understanding of the consequences of implementing different ERA options.

While each retrofitting case is unique, they all need to consider the capital cost support and payback periods, which are the most challenging factors for ERAs. Moreover, residents struggle with increasing electricity prices, which could incentivize them to accept energy upgrade measures without capital costs. This chapter builds on the scenarios presented in the previous chapters and outlines applicable application models that can help decision-makers to understand the potential investment models and their effects on payback options.

To achieve this goal, a mixed-method analysis (qualitative and quantitative) was conducted, considering energy-saving options and a cost–benefit analysis. Various study models were developed to illustrate the potential outcomes of different ERA options. Section 6.2 highlights the challenges of implementing ERAs in Jeddah city, while Section 6.3 defines the beneficiaries and their roles. Section 6.4 presents a decision-making approach to the problem, while Section 6.5 calculates the potential energy savings and CO2 emission reductions, capital costs, and payback periods on a city-wide level. Section 6.6 elaborates on different study models to illustrate the short- and long-term consequences and discusses alternative possibilities. Finally, Section 6.7 presents the main outcomes and conclusions. Figure 6.1 illustrates the chapter outline.

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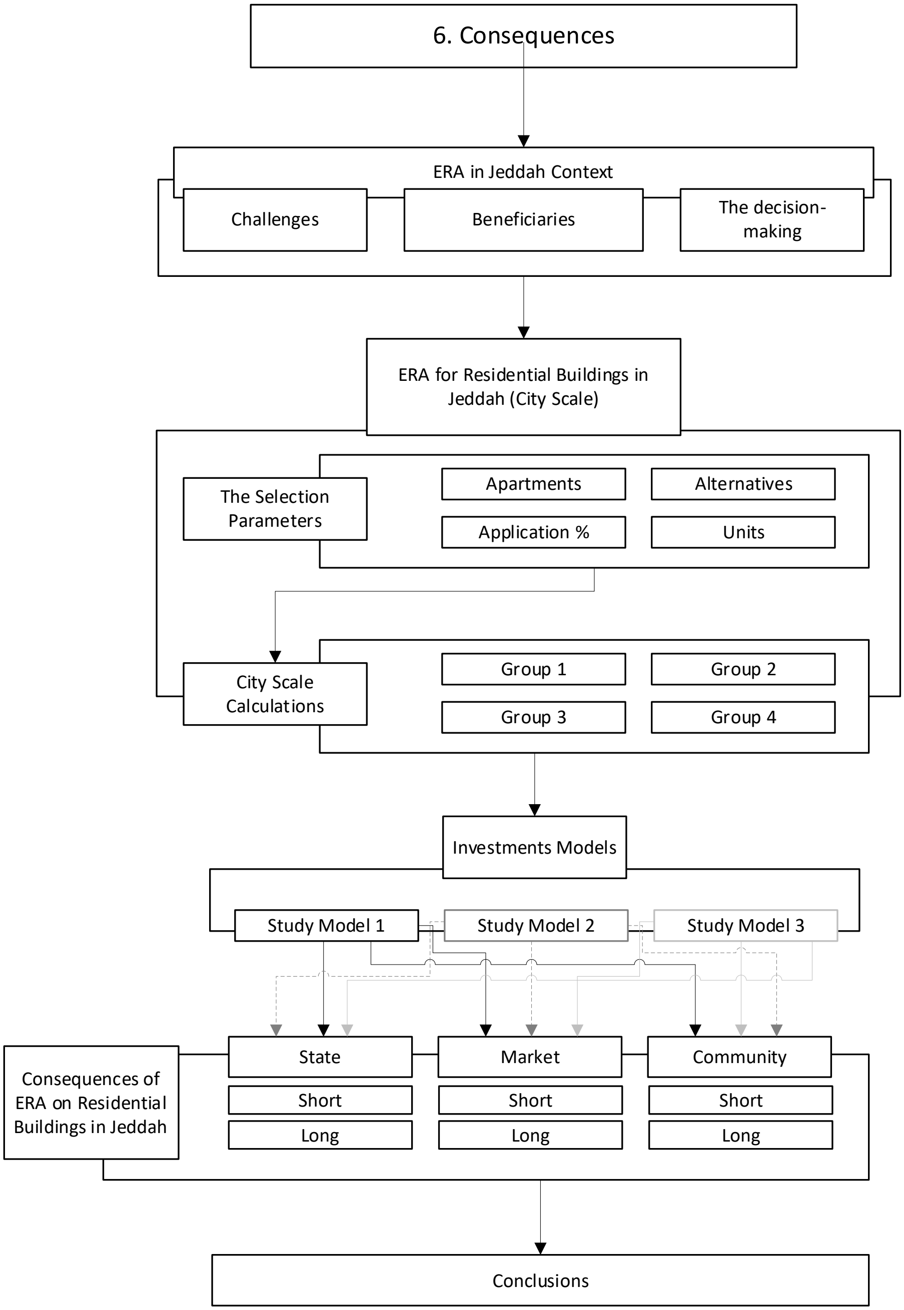

FIG. 6.1 Chapter 6 outline structure.

6.2 ERA Challenges in the Jeddah Context

Comprehensive research has identified various challenges that hinder the energy-efficient retrofitting of existing residential buildings, including stakeholder priorities, time constraints, capital investment, cost-effectiveness, risk analysis, technology availability, government policies, building energy, and performance prediction [28], [34], [36]. This study emphasizes the need for a detailed investigation of the energy-saving profile using energy retrofitting, considering current ERA for existing buildings policies and suggesting potential changes to these policies, the user needs, and the cost–benefit analysis.

The challenges facing ERAs have been divided into four types: environmental, social, economic, and governance challenges, each of which has a different impact on ERAs in the Jeddah context. Environmental challenges represent the central issue, as high energy consumption increases CO2 emissions, ranking Saudi Arabia 8th in respect of the worst carbon dioxide emissions per capita worldwide [146]. This chapter focuses on the long-term effect of ERAs on CO2 emission reduction at the Jeddah city level and how ERAs can be an investment opportunity for the state if applied to the total residential stock of more than 5.5 million housing units.

Social challenges include persuading unit owners and tenants to accept ERA implementation methods, as the primary consideration for building users in the KSA context is the increasing monthly electricity bills, especially in the summer. This chapter elaborates on the main constraints regarding user acceptance and suggests possible incentives that might increase their acceptance.

Economic challenges entail determining the capital investment source and cost-effective plans, including payback periods, which support policymakers in constructing effective ERA policies. The study identifies the total capital investments and payback time as key indicators, considering different compensation possibilities.

Governance challenges involve organizing and prioritizing stakeholders' needs, requiring numerous action policies that comply with these needs. The study draws attention to the possibility of upgrading or creating new or updated managerial action policies, which will need further investigation.

This research aims to develop suitable ERA cases at the city level using a method that could be applied to other cities in the country. This chapter demonstrates different study models and possibilities depending on the housing unit's needs, such as location and energy performance.

6.3 Beneficiaries of the ERA in the Jeddah Context

In residential building design and construction, energy retrofitting applications (ERAs) offer benefits to multiple parties, namely the state, market actors, and the community [147]. The state benefits from developing regulations and policies for energy-efficient buildings supported by programs and incentives. Municipalities or cities, federal or national governmental bodies, and public agencies or institutions represent the state's interests. Effective policies and support are essential for successfully implementing energy efficiency measures, including administrative and financial aspects [36], [147]. The former involves identifying suitable options for the different housing ownership types, while the latter considers the financial status and available alternatives.

Market actors, including planning and construction parties, urban planners, architects, product and technology suppliers, distribution system operators, energy supply companies, and financing intermediaries, also benefit from residential building energy efficiency [36], [147]. They can improve the quality of their services, such as designing, constructing, and maintaining housing units. The provision of building energy products and services is a key role of market actors.

The community also benefits from increased residential building energy efficiency, particularly in providing an acceptable range of indoor thermal comfort [36], [147]. Building owners, housing associations or companies, private housing companies, real estate companies, public or social housing actors, and resident or neighborhood associations represent the community. Their primary role is to ensure that building users are satisfied with the thermal comfort and electricity bills while promoting energy efficiency awareness among users.

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6.4 ERA decision-making within the KSA Context

Proposing ERAs for residential housing in a representative city (Jeddah) is essential for an energy upgrade. As explained in previous chapters, Jeddah city was used as a case study due to its high cooling demand challenges; other cities in the country could also benefit from the method used. The aim of this chapter is to help decision-makers support the execution of ERAs. Furthermore, deciding which action policy to execute could differentiate the ERA consequences. To help decision-makers choose a suitable case, this chapter introduces decision-making levels to answer the critical questions within each level.

6.5 ERA calculations for Jeddah City

In the preceding chapters, calculations were performed at the unit level, while in this section, the focus is on the city level, considering the entire mid-rise residential stock in Jeddah city. The primary objective of this study is to investigate the impact of ERAs on energy savings, capital costs, and payback periods, particularly emphasizing the environmental, economic, and social consequences. Short-term and long-term consequences have been identified using the same aspects for different study models.

To explore the consequences of ERAs, several significant parameters have been defined, including the decision-maker (the state), three key-performance indicators (capital investment, payback years, and yearly energy savings), and various scenarios that affect the action plans when choosing one over the other. The results of the previous chapters have been used and applied on a larger scale (city scale) to define the possible scenarios and predict the ERA consequences.

The city-level calculation takes into account several parameters, including case selection (representative apartments and intervention type), application percentage, scenario name coding, capital costs (at different interest rates), oil selling (from energy savings), payback periods, and CO2 emission reductions.

The case selection is based on the different outcomes from the previous results, where apartment 1 represents 75% of the mid-rise residential unit stock, and apartment 8 represents the remaining 25%. The interventions include indoor and outdoor types, with air tightening and thermal insulation, and with window replacement being the most suitable approach for energy-efficient retrofitting. Different scenarios are included, with the applicable percentage divided into three levels (50%, 75%, and 100%) to provide flexibility for the suggested different models. In addition, the oil sales results are displayed on a separate axis on the graph's right side for Figures 6.2, 6.3, 6.4, 6.5. Therefore, a coding system is initiated for the suggested scenarios to facilitate discussions, analysis, and future model designs, with each case having two numbers and a letter (number-number-letter). The first number represents the scenario number, the middle number represents the apartment number, and the letter represents the application percentage as shown in Tables 6.1 and 6.2.

The calculation considers the entire mid-rise residential stock (around 600,000 housing units) in Jeddah, calculating the total investment's capital costs and interest rates affected by presenting its reflection on the payback periods [51]. The payback calculation considers an alternative 6 payback scenario and considers the energy savings reduction by adding the oil sales from the energy savings. The projections of how much oil will be sold are also included in each case. Table 6.3 illustrates the key indicator units used in the study.

TABLE 6.1 Description of Coding Numbers for Indoor Scenarios.

Indoor Scenarios			
#	Details	#	Details
11A	Scenario 1, Apartment 1, 100% application	18A	Scenario 1, Apartment 8, 100% application
51A	Scenario 5, Apartment 1, 100% application	58A	Scenario 5, Apartment 8, 100% application
71A	Scenario 7, Apartment 1, 100% application	78A	Scenario 7, Apartment 8, 100% application
91A	Scenario 9, Apartment 1, 100% application	98A	Scenario 9, Apartment 8, 100% application
11B	Scenario 1, Apartment 1, 75% application	18B	Scenario 1, Apartment 8, 75% application
51B	Scenario 5, Apartment 1, 75% application	58B	Scenario 5, Apartment 8, 75% application
71B	Scenario 7, Apartment 1, 75% application	78B	Scenario 7, Apartment 8, 75% application
91B	Scenario 9, Apartment 1, 75% application	98B	Scenario 9, Apartment 8, 75% application
11C	Scenario 1, Apartment 1, 50% application	18C	Scenario 1, Apartment 8, 50% application
51C	Scenario 5, Apartment 1, 50% application	58C	Scenario 5, Apartment 8, 50% application
71C	Scenario 7, Apartment 1, 50% application	78C	Scenario 7, Apartment 8, 50% application
91C	Scenario 9, Apartment 1, 50% application	98C	Scenario 9, Apartment 8, 50% application
	Description		
Scenario1	Mortar Finishing + replace Windows (Creative Windows CO.)		
Scenario5	Wall (XPS 10 cm)(HFC)+ Mortar Finishing		
Scenario7	Wall (XPS 10 cm)(HFC)+ Mortar Finishing + replace Windows (Creative Windows CO.)		
Scenario9	Wall (XPS 10 cm)(HFC)+ Mortar Finishing + replace Windows (Creative Windows CO.) + Upgrade roof with XPS 15cm		
Apartment 1	A representative case for apartments (1,2,3,4,5,6)		
Apartment 8	A representative case for apartments (7 and 8)		
% Application	Scenario application percentage in Jeddah city		

TABLE 6.2 Description of Coding Numbers for Outdoor Scenarios.

Outdoor Scenarios			
#	Details		
11A	Scenario 1, Apartment 1, 100% application	18A	Scenario 1, Apartment 8, 100% application
41A	Scenario 4, Apartment 1, 100% application	48A	Scenario 4, Apartment 8, 100% application
61A	Scenario 6, Apartment 1, 100% application	68A	Scenario 6, Apartment 8, 100% application
11B	Scenario 1, Apartment 1, 75% application	18B	Scenario 1, Apartment 8, 75% application
41B	Scenario 4, Apartment 1, 75% application	48B	Scenario 4, Apartment 8, 75% application
61B	Scenario 6, Apartment 1, 75% application	68B	Scenario 6, Apartment 8, 75% application
11C	Scenario 1, Apartment 1, 50% application	18C	Scenario 1, Apartment 8, 50% application
41C	Scenario 4, Apartment 1, 50% application	48C	Scenario 4, Apartment 8, 50% application
61C	Scenario 6, Apartment 1, 50% application	68C	Scenario 6, Apartment 8, 50% application
	Description		
Scenario1	EIFS Wall (EPS 10cm)		
Scenario4	EIFS Wall (XPS 10cm)+ replace Windows (Creative Windows CO.)		
Scenario6	EIFS Wall (XPS 10cm)+ replace Windows (Creative Windows CO.) + Upgrade roof with XPS 15cm		
Apartment 1	A representative case for apartments (1,2,3,4,5,6)		
Apartment 8	A representative case for apartments (7 and 8)		
% Application	Scenario application percentage in Jeddah city		

TABLE 6.3 Key indicator units.

KPI	Unit
Energy Savings	TWh/year
CO2 emissions	Billion kg CO2e/year
Oil SALES	USD billions/year
Payback period	Years
Capital Cost	USD billions
Savings per Apt	USD/year

The results of the calculations were categorized into four groups, with each case having nine outcomes. The outcomes within each group, which corresponded to a specific apartment and intervention type, were compared, and the best result was identified. Each group was then presented separately in a graph and thoroughly discussed in the study model section. In general, the graphs are divided into three study models.

A Group 1 (Apartment 1_Indoor Scenarios 1,5,7,9, Application 100%, 75%, 50%)

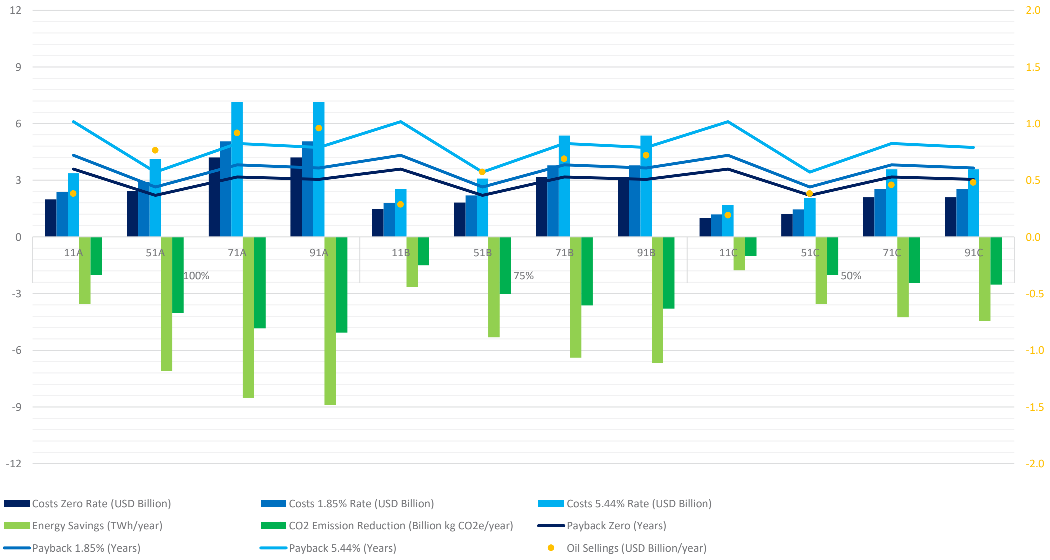

FIG. 6.2 Calculation of key performance indicators (KPIs) for apartment 1 across four selected indoor scenarios.

Figure 6.2 presents the results for Group 1, which focuses on indoor interventions for apartment 1, representing 75% of Jeddah's building stock. The 91A Scenario provides the highest energy savings of 8.9 TWh/year and has the highest total capital cost of 4.21 billion USD (at zero interest rate), resulting in the highest oil sales of around 1 billion USD. The savings per apartment are just below 2050 USD/year, and the payback time is approximately three years. In contrast, Scenario 51B (with 75% application) is a better option regarding energy savings, capital cost, oil sales, and payback years compared to Scenario 11A (with 100% application), as depicted in Figure 6.2. However, 25% of the building stock remains without enhancement, allowing other scenarios to be applied.

Additionally, the 50% application options offer another alternative for decision-makers to divide the application into two time periods or different scenarios. The selection of application scenarios in the current case in Jeddah depends on the study model's goals, which will be explained in more detail in Section 6.6.

B Group 2 (Apartment 8_ Indoor Scenarios 1,5,7,9, Application 100%, 75%, 50%)

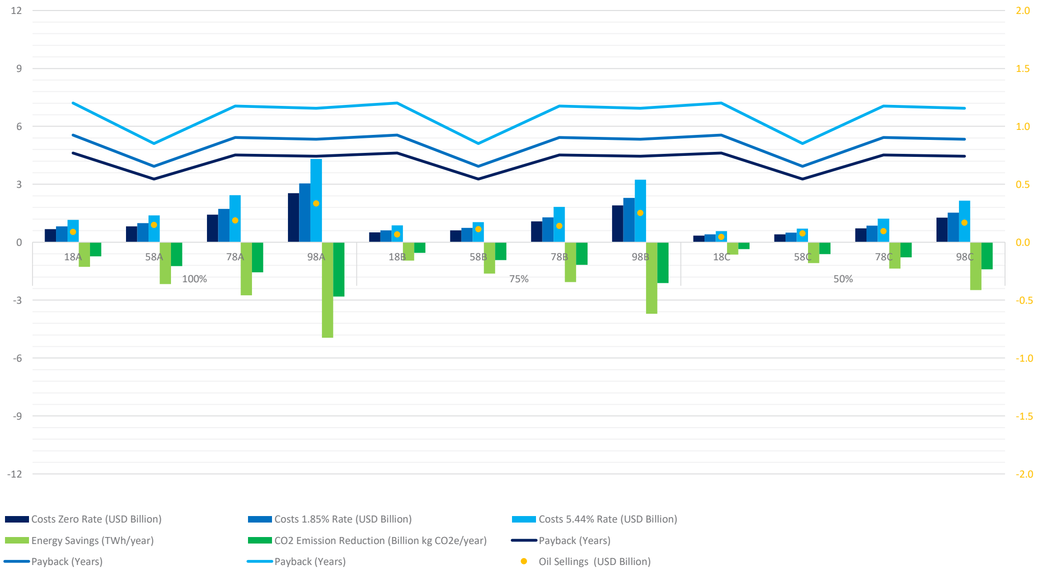

FIG. 6.3 Calculation of key performance indicators (KPIs) for apartment 8 across four selected indoor scenarios.

Figure 6.3 depicts Group 2, presenting various scenarios for apartment 8, constituting 25% of the building stock in Jeddah, utilizing multiple indoor interventions. 98A yields notable savings results among these scenarios, as the figure demonstrates. Additionally, Figure 6.3 exhibits the least compelling scenario for indoor interventions, with only 1.3 TWh/y in energy savings and a more extended payback period of over seven years.

C Group 3 (Apartment 1_Outdoor Scenarios 1,4,6, Application 100%, 75%, 50%)

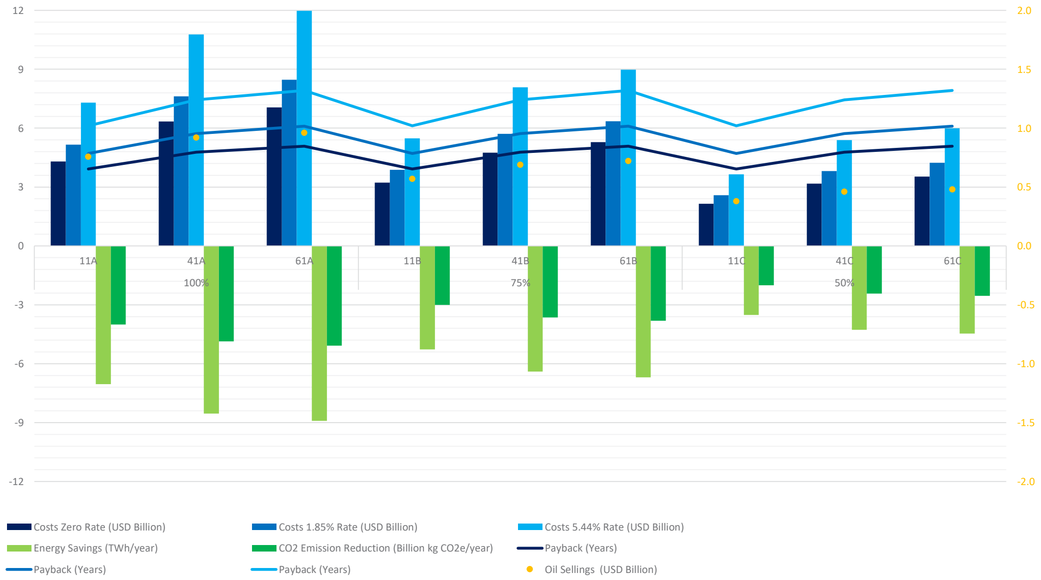

FIG. 6.4 Calculation of key performance indicators (KPIs) for apartment 1 across three selected outdoor scenarios.

Group 3, as illustrated in Figure 6.4, displays various options for multi-outdoor interventions in apartment 1 (constituting 75% of the building stock in Jeddah). The scenarios present competitive savings results, particularly Scenarios 4 and 6, with varying application percentages. More advanced intervention yields more significant savings at the expense of higher capital costs and extended payback years. Figure 6.4 highlights multiple opportunities for savings with different payback alternatives, all of which rely on investment decisions and the objective of attaining the ERA goal.

D Group 4 (Apartment 8_Outdoor Scenarios 1,4,6, Application 100%, 75%, 50%)

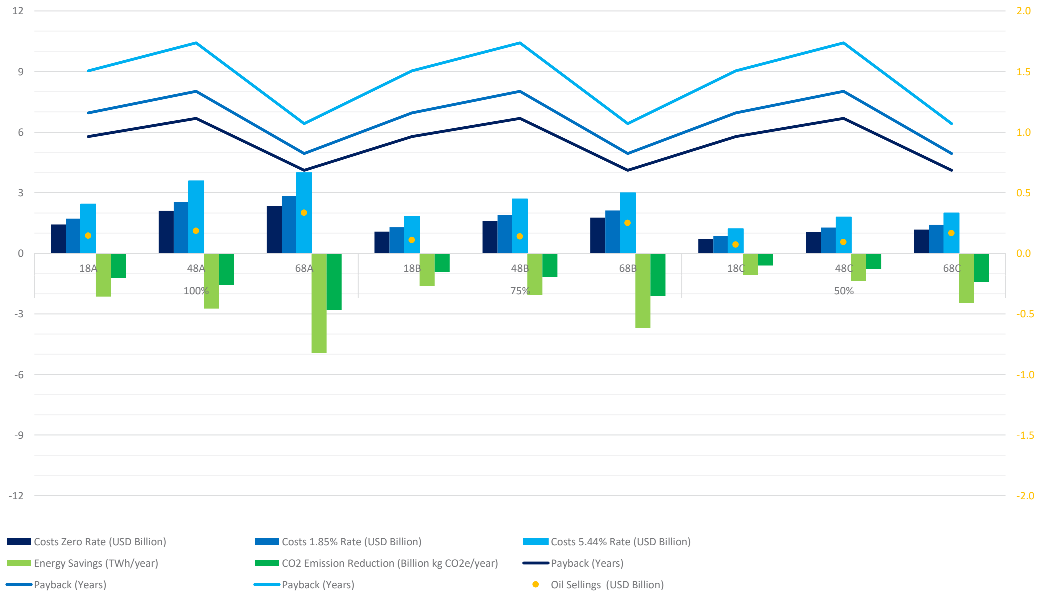

FIG. 6.5 Calculation of key performance indicators (KPIs) for apartment 8 across three selected outdoor scenarios.

In Figure 6.5, Group 4 is presented, which displays various options for apartment 8 (25% of the building stock in Jeddah) with multi-outdoor interventions. The results indicate that Scenario 6 offers substantial savings and the shortest payback period in the same group. Furthermore, the outcomes of Scenario 68A are noteworthy, demonstrating the highest savings with the highest capital cost but a shorter payback period compared to Scenario 48A.

To summarize, the calculations of different scenarios for different parameters (energy savings, capital cost, payback periods, and oil savings) provide a range of possibilities for energy upgrades with different investment possibilities. Therefore, the following section highlights the different ERA aims in order to determine suitable possibilities for the targeted goals.

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6.6 ERA Study Models

This section describes three distinct study models for residential building ERAs to determine each model's short- and long-term consequences. The goals of each study model were defined using parameters such as the source of capital cost, level of energy savings, and payback periods that would result in specific consequences. These study models were based on three different investment models: governmental, private investment (bank/developer), or mixed investment (private + governmental). Each model's payback period and energy savings were also calculated using the alternative 6 payback method, as mentioned in Chapter 5. The payback period was capped at five years, which aligns with the current payback periods set by the Social Development Bank (SDB). However, in cases where the proposed outcomes failed to meet the payback cap, other options were selected to provide relevant results.

In all cases, the government pays the total investment with one of three options: directly to the contractors in one payment, paying the bank in settlements, or paying in two parts (down payments and settlements). The proposal is intended to give an overview of the possible economic and environmental investment options. Furthermore, each group of cases addresses specific study model aims. Furthermore, the number in the case name indicates the model number, the decimal number indicates the intervention type (0.1 for indoor and 0.2 for outdoor), and the letter indicates the model condition of the potential scenario.

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A Study model 1

The first study model focused on governmental investment, where the total capital cost relied on governmental supporting fund programs. The primary outcomes of this model were to show the differences in the total investment and the payback period ranges of the selected scenarios (indoor or outdoor interventions), as shown in Table 6.4. The decision selection was based on rules of a maximum 5-year payback period and the highest energy savings.

TABLE 6.4 Calculation of oil selling, energy savings, and CO2 reduction for study model 1.

Model 1	Case	Energy Savings			Case	Energy Savings		
		64%	67%	Total		64%	67%	Total
Scenarios	**1.1**	**91A**	**98A**		**1.2**	**61A**	**68A**	
Zero Rate (USD B)		4.2	2.5	6.7		7.1	2.4	9.4
Payback Years		3.0	4.5			5.1	4.1	
Oil Sales (USD Billion/year)				1.3				1.3
Energy Savings (TWh/year)				-13.8				-13.9
CO2e Reduction (Billion kg CO2e/year)				-7.9				-7.9

Initially, scenarios 91A and 98A were selected for indoor interventions (case 1.1). Both scenarios provided the highest energy savings in the indoor interventions at 13.8 TWh/y, ranging between 3 and 4.5 years of payback time. The total investment was just above 6.5 billion USD, with a yearly oil sale of just above 1.3 billion USD. Applying case 1.1 for the whole residential (mid-rise) stock in Jeddah resulted in a yearly reduction of just below 8 billion kg CO_2e.

Scenarios 61A and 68A were the selected scenarios for the outdoor interventions (case 1.2). Both scenarios showed significant savings, the same as the 91A and 98A Scenarios but with a higher cost of just below 9.5 billion USD and a slightly higher range of payback periods between 4 and 5 years.

However, there were several differences between both cases. The main difference was the application, where case 1.1 could only be performed individually (unit level), while case 1.2 could be performed at the building level and individually if unit owners agreed to apply the energy upgrade simultaneously. Case 1.2 distributed an equal capital cost for every unit in the same building, while case 1.1 had different capital costs for each unit. The capital cost was around 3 billion USD higher for case 1.2, with about a year longer payback time. In addition, the monthly electricity consumption was estimated to reach 64% and 67% of energy savings for cases 1.1 and 1.2.

B Study model 2

The second study model focused on private investment, where the total cost was attributed to the banks or developers, which allowed profit for a third party. However, the primary outcomes of this model were to determine which case worked best for this study model in terms of total investment and the payback period ranges of the selected scenarios (indoor or outdoor interventions). The selection was based on the highest energy savings with no maximum payback periods.

Table 6.5 illustrates cases 2.1A and 2.2A, with similar energy savings to cases 1.1 and 1.2 but with a higher capital cost and additional years for payback times. The cases with a 1.85% interest rate (2.1A and 2.2A) had an additional payback period of around one year and additional capital costs of 1.5 and 2 billion USD, respectively, compared to study model 1 (1.1 and 1.2). Likewise, the 5.44% interest rate cases (2.1B and 2.2B) added extra capital costs of 4.7 and 6.6 billion USD, respectively, and additional payback periods of 2-3 years compared to study model 1.

In the same model, the change only adjusted the payback periods to a maximum of 5 years, but the other conditions remained the same. The selection for possible cases was less efficient, at just below 15% and 40%, than for cases 2.1 (A and B) and 2.2 (A and B). Therefore, the total energy saving decreased by around 15-20%, and the total cost decreased by just above 15% compared to cases A and B. The lowest payback period of case 2.2D was above six years, which was impossible to apply as it was decided to only use scenarios with a payback time of five years or less, as shown in Table 6.6.

TABLE 6.5 Calculation of oil selling, energy savings, and CO2 reduction for study model 2 (A, B).

Model 2	Case	Energy Savings			Case	Energy Savings		
		64%	67%	Total		64%	67%	Total
Scenarios	**2.1A**	**91A**	**98A**		**2.2A**	**61A**	**68A**	
+1.85% Rate (USD B)		5.1	3.1	8.1		8.5	2.8	11.3
Payback Years		3.7	5.3			6.1	4.9	
Scenarios	**2.1B**	**91A**	**98A**		**2.2B**	**61A**	**68A**	
+5.44% Rate (USD B)		7.1	4.3	11.5		12.0	4.0	16.0
Payback Years		4.7	6.9			7.9	6.4	
Oil Sales (USD Billion/year)				1.3				1.3
Energy Savings (TWh/year)				-13.8				-13.9
CO2e Reduction (Billion kg CO2e/year)				-7.9				-7.9

TABLE 6.6 Calculation of oil selling, energy savings, and CO2 reduction for study model 2 (C, D).

Model 2	Case	Energy Savings			Case	Energy Savings		
		64%	29%	Total		50%	67%	Total
Scenarios	**2.1C**	**91A**	**58A**		**2.2C**	**11A**	**68A**	
+1.85% Rate (USD B)		5.1	1.0	6.0		5.2	2.8	8.0
Payback Years		3.7	3.9			4.7	4.9	
Scenarios	**2.1D**	**91A**	**58A**		**2.2D**	**11A**	**68A**	
+5.44% Rate (USD B)		7.0	1.4	8.4		7.3	4.0	11.3
Payback Years		4.7	5.1			6.1	6.4	
Oil Sales (USD Billion/year)				1.1				1.1
Energy Savings (TWh/year)				-11.1				-12.0
CO2e Reduction (Billion kg CO2e/year)				-6.3				-6.8

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C Study model 3

The third study model focused on mixed investments (private and governmental), where the total costs were attributed to the banks or developers but with governmental support (covering additional costs like interest), as shown in Table 6.7. The concept was to incentivize building owners to subsidize the initial cost of the ERA [17]. This case model was taken from an existing case model from the housing ministry programs (first house). In this model, the state pays the added interest percentage to the bank/developer while the citizen pays back the original loan to the bank [39]. Thus, the state pays the profit up front to the private investor. However, the primary outcomes of this model were to determine which case works best in terms of the capital cost paid by the state and the payback period ranges of the selected scenarios (indoor or outdoor interventions). The selection was based on the highest energy savings with 5-year maximum payback periods.

TABLE 6.7 Calculation of oil selling, energy savings, and CO2 reduction for study model 3 (A, B).

Model 3	Case	Energy Savings				Case	Energy Savings			
		64%	67%	Total	Gov pay		64%	67%	Total	Gov pay
Scenarios	**3.1A**	**91A**	**98A**			**3.2A**	**61A**	**68A**		
+1.85% Rate (USD B)		5.1	3.1	8.1	1.4		8.5	2.8	11.3	1.9
Payback Years		3.0	4.5				5.1	4.1		
Scenarios	**3.1B**	**91A**	**98A**			**3.2B**	**61A**	**68A**		
+5.44% Rate (USD B)		7.1	4.3	11.5	4.7		12.0	4.0	16.0	6.6
Payback Years		3.0	4.5				5.1	4.1		
Oil Sales (USD Billion/year)				1.3					1.3	
Energy Savings (TWh/year)				-13.8					-13.9	
CO2e Reduction (Billion kg CO2e/year)				-7.9					-7.9	

The table shows a significant reduction in capital costs for cases 3.1A and 3.2A that the state will pay, which are around 1.5 and 2 billion USD compared to the zero interest cases. In cases 3.1B and 3.2B, the state's capital costs were less than 50% and 30%, respectively, which might not be favorable for the total cost investment, especially when selecting alternative 6 for payback.

The study has illustrated different ERA study models to determine the differences between different case models at the city level. The calculated cases used only 100% of the application, while 75% and 50% were calculated to provide other options. For instance, using 50% of the application for case 1.2 could allow using cases 2.1A or 2.1B for the other 50%, and other mixed solutions could be investigated.

FIG. 6.6 Comparison between different indoor and outdoor cases.

Figure 6.6 summarizes and compares different cases regarding the total investment, yearly CO2 reduction, yearly oil selling, and the payback periods. The outcomes present different variations in payback that depend on the selected scenario and the total investment cost. For instance, in Figure 6.6, apartment 1 has shorter payback periods when selecting indoor cases than outdoor cases. In contrast, apartment 8 has shorter payback periods in most outdoor cases compared to indoor cases. The results indicate the relation between the payback and the investment option, as this depends on each individual case. Hence, designing an appropriate ERA case would involve determining the available ERA possibilities in terms of funding, energy upgrade measures, and payback periods.

6.7 Discussion of the long- and short-term consequences of ERAs

This section illustrates short- and long-term ERA consequences and the study models are used to demonstrate the different effects. The short-term consequences are concentrated on the actions needed to make the ERA occur. The long-term consequences focus on ERA effects on Jeddah's whole residential building stock. The main aim was to project possible ERA consequences on the ERA beneficiaries (state, market, and community).

6.7.1 The State

The critical consequence of ERAs on existing residential buildings at the state level is to create and update action policies (long-term) to help obtain the national 2060 goal of net-zero emissions [72], [132]. This requires constant research and development to provide appropriate action policies. Subsequently, the action policies have to include specific standards of energy efficiency levels. The levels depend on selecting which ERA models most suit the focused context (city level).

The action policies need to update or create regulations for energy efficiency (energy standards) for existing residential (mid-rise) buildings. For instance, after 2035, all residential units exceeding 100 kWh/m^2 will have 200% extra electricity tariffs. Alternatively, the residential units that use ERAs and are below 100 kWh/m^2 could receive a 50% reduction in electricity tariffs. However, in both examples, the deadline year and the level of energy consumption per square meter need to be investigated and developed to provide up-to-date specific energy benchmarks and standards.

Correspondingly, the action policies have to provide designed funding programs (governmental, private, or a mixture of private and governmental) that fit the focused context to ensure the economic aspects. Funding programs must consider the capital cost, payback periods, payback methods, energy savings, oil savings, and CO2 emission reduction.

Several consequences for the different study models have been provided in Section 6.6.2. In model 1, the selected cases were promising in terms of low payback periods and high energy savings, as the model reduces energy consumption by around 14 TWh/year as a long-term consequence. Nevertheless, the model requires a total governmental capital cost (short consequence) of around 7 or 10 USD billion for Jeddah city alone, which could be 70 or 100 USD billion for the KSA as Jeddah accounts for 10% of the total residential building (mid-rise) stock.

In addition, the oil sold from the electricity savings (burned from oil) was around 1.3 USD billion yearly, a long-term consequence. In the same model, as a long-term consequence, the CO2 emission reduction would reach just below 8 billion kg CO2e yearly. Before and during the application of ERAs, a benchmark of the electricity consumption range per square meter has to be set and developed. Hence, cases 1.1 and 1.2 of model 1 promise energy savings, short payback periods, and the lowest capital costs, but will require a massive investment from the state, requiring a high energy upgrade budget.

In model 2, the private investor rather than the state pays the capital cost, which results in more extended payback periods. There are two types of cases: the first cases (2.1A, 2.2A, 2.1B, and 2.2B) have similar savings to model 1 but with an additional 20% in terms of payback years for a 1.85% rate and just above 55% for a 5.44% rate, and increasing 20% and 70% of the total costs compared to model 1. Different savings ranges were calculated for the other type of cases (2.1C, 2.2C, 2.1D, and 2.2D) that required a maximum of 5 years of payback time. The total energy savings were reduced by 20% for cases 2.1C and 2.1D and just under 15% for cases 2.2C and 2.2D compared to cases 1.1 and 1.2.

The yearly oil sales decreased by about 15% compared to model 1. However, in model 2, case 2.2D could not be applied because of the 5-year payback time limit and the high interest rate. When the state pays zero for the capital cost, and the private investor pays the capital cost, and this escalates the total costs, which causes a payback period of longer than 5 years.

Model 3's savings and payback periods were similar to those of model 1. The state pays less capital costs for cases 3.1A, 3.2A, 3.1B, and 3.2B than model 1. The state pays only 20% of the capital costs at a 1.85% rate and 70% at a 5.44% rate, while the private investor pays the rest. Therefore, model 3 is only feasible when a low interest rate is added (1.85%), while a 5.44% rate would not be feasible regarding total cost investment. The feasibility of the cases would depend on the selected action policies.

In brief, it is possible to design numerous cases with different consequences. The state needs to justify the main objectives of ERAs to select the most feasible and applicable cases to predict the consequences of the chosen scenarios.

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Generally, the state mainly benefits from ERAs in terms of keeping energy standards and current policies up-to-date. In addition, ERAs on a national level could significantly affect the energy efficiency in respect of buildings' energy performance. At the same level, energy performance standardization for buildings would help reach the 2060 net-zero emissions goal by lowering buildings' CO2 emissions.

6.7.2 The Market

The market is considered to be a service provider; the market representatives are designers, product suppliers, constructors, and financial investors. The market representatives are affected by ERA aspects, such as research and development (R&D), energy policies (consumption level), new revenue, and quality. The state selection of action plans to implement ERAs would require different actions from the market representatives to create the long-term effects.

Initially, the energy efficiency standards require the designers (architectural firms) to consider energy designers in their design team for ERAs to reach the standard level of energy consumption. The energy designer's team would be required to follow each ERA's sustainable building retrofit program steps. However, Zhenjun outlined the key phases of a systematic, sustainable building retrofit program that could be used for ERAs, and the study suggested conducting additional research on energy retrofitting strategies in light of the human factor and ERA uncertainty [28].

ERA designers need to continuously research and develop various methods to improve energy efficiency levels. Chapters 3-5 discussed several concerns about designing ERA scenarios, including collaboration with market representatives, simulation inputs, pricing, construction methods, and implementation. The lack of research on ERAs can be attributed to the recent introduction of energy efficiency in 2018, which became more widely known after VAT was increased to 15% in July 2020. Chapter 4 highlighted the importance of air changes per hour (ACH) as an essential indicator for accurately simulating housing units. However, current ACH research is insufficient and requires further investigation to obtain accurate ACH levels. Additionally, the time activity schedule for designated units can impact scenario selection, and involving building users in the ERA process can aid energy designers in making the best decisions. Thus, ERAs require guidelines for evaluating and assessing each housing unit using actual testing.

The specialty of energy efficiency will create new job opportunities in the market. According to the IEA, building efficiency retrofitting for sustainable recovery plans could create nearly 15 jobs for every 1 million USD invested, emphasizing the significance of this field [80], [148]. In study model 1 for Jeddah, case 1.1 is expected to create around 100,000 jobs, and case 1.2 will generate just below 140,000 jobs. Designers must be actively involved in creating and updating energy policy standards, contributing their knowledge and experience in energy consumption levels, including AAEC, ACH, and thermal comfort range. Energy efficiency certificates or relevant experience may be necessary for designers to meet specific qualifications and ensure a certain level of quality.

Moreover, product suppliers (e.g., insulation, windows, blocks, sealants) must be thoroughly researched, and good quality, effective, and efficient materials at a reasonable price must be selected from the local context. Materials standards must be updated and included in ERA energy policies, which require a certain level of quality. Involving designers and construction companies in product development can lead to better-quality energy-performance materials at a lower cost than imported ones [36], [147]. A list of the most basic required materials can guide users and designers toward the best ERA. Product suppliers must avoid low-quality materials and provide efficient ones to increase their availability, creating more jobs in the materials industry.

Construction companies must develop construction methods that comply with ERA materials regulations and standards, ensuring quality and capacity. Investigating current constructors' capacity levels and evaluating their quality is necessary to define ERA implementation. Special training should be implemented to retrofit buildings to given standards, and trained personnel should receive specific qualifications to practice ERA standards incorporating energy policy actions. Construction companies must implement higher standards of energy enhancement and be involved in updating ERA energy policy actions.

Furthermore, the number of financial investors will increase as more ERA projects are needed. Financial investors (governmental or private) must familiarize themselves with ERA financial plans. Different economic investment models can be created depending on the local context, requiring governmental support, especially in the beginning stages of introducing ERAs. After setting the 2060 net-zero goal, economic investors can develop efficient solutions, such as net-zero buildings or selling energy to the grid. Economic investment models should be included in ERA energy policy actions.

Market representatives must follow the energy policy standards, and implementing energy efficiency qualifications is crucial to maintain best quality practices for ERAs. Evaluating and testing actual projects and setting specific processes and quality indicators will increase market representatives' credibility. Energy standards can eliminate low- or poor-quality providers or help develop them to meet the set standards. ERAs will create job opportunities specializing in energy efficiency, supporting their existence.

6.7.3 The community

The leading representatives of the community are the building users. Initially, building users need to accept the ERA ruling and what is required to meet each case's needs. The designers (on behalf of the market representatives) need to explain in layman's terms what the energy savings will be and how the retrofitting will substantially reduce the users' monthly bills. In addition, using an actual case model of two units (one having applied the ERA retrofitting measures and the other one representing the current case) is a good way to let the potential retrofitting clients experience first-hand what the difference is, clearly explaining to them what to expect in terms of thermal comfort and how much the energy consumption level will change, and what that change will represent in terms of monthly energy expenditure. To reiterate, users need physical evidence and an understanding of the benefits of ERAs in respect of residential buildings.

During construction, users will be disturbed by whatever sort of retrofitting is chosen. Outdoor interventions will result in less disturbance than indoor interventions as there will be less contact with building users. However, investigating the difference between both interventions is essential in selecting which ERA case is appropriate, as different activities are required depending on every case.

The users' awareness of the importance of energy efficiency will increase as they recognize the considerable savings in their monthly energy consumption and how that could impact the national energy consumption level. Users will become more aware of how their daily activities affect their electricity bills, as they can lower their energy bills simply by changing different behavior patterns coupled with the ERA.

However, communication is a key factor, and the users will accept the ERA with open arms if everything is clearly explained. The results must be explicitly shown and well delivered, and the physical project could greatly help to achieve this. Introducing energy efficiency for users is essential to implement ERAs for existing buildings.

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The long-term consequences of the ERA could also be clarified to users, which could help increase their acceptance of the ERA. The main long-term consequence for the user is the reduction in the price of their electricity bills, which would require a case-by-case calculation to predict the exact reduction percentage and the indoor space's thermal comfort level. For instance, the market representative should demonstrate the effect of the infiltration rate in a simulation program and let the user see it in an actual project. In addition, one of the critical consequences of the ERA is increasing the quality of the building. Furthermore, after the building has been retrofitted, the lifespan of the building will be extended, which will also impact the resale value of the unit as it is being maintained. Reaching an efficient energy level would also increase the resale value of the unit as the building will be more energy-efficient compared to other units.

The study models that have been illustrated have different consequences for the users if the person responsible for the payback is the only user. The payback years will be a significant variable as the cheapest case with high energy savings is most preferable.

There are various broader long-term consequences of ERAs on residential buildings when applying the same methods to other regions in the KSA. Primarily, the state would have a standard range of energy consumption levels per square meter for each region in the KSA. That would create a general understanding of energy consumption levels for units' energy performance. An energy labeling code could be initiated, and the electricity bill range could be demonstrated based on the labeling code. That would create a pricing indicator for housing units. In addition, architectural firms, including energy designers, would be more reliable in designing units with energy-efficient standards. However, this will require user awareness of energy efficiency, which could be gained from an energy labeling code. Hence, ERAs are essential for current housing units to promote energy efficiency.

6.8 Conclusions

In this chapter, the consequences of ERAs on residential buildings were analyzed and investigated at the city level using Jeddah as a representative case study.
The chapter's main idea was to define and describe the short- and the long-term consequences to help state decision-makers execute ERAs for residential buildings in Jeddah. The main indicators were the investment source of the capital cost, energy savings, CO2 reduction, and payback periods.

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The chapter indicated the importance of defining different parameters and challenges of ERAs. In addition, the ERA beneficiaries were presented to direct the study models. However, the calculations were limited to two representative apartments (1 and 8) and particular scenarios. Thus, samples were presented that will be further detailed in an actual case.

Specific scenarios (high in energy savings) were selected for further calculations in the study model section. The analysis of study models provided various cases that allow decision-makers to select appropriate cases based on their targets. The results highlighted the impact of the investment source and the selected scenarios on the payback periods. The results show that each case would need individual analysis to determine an appropriate ERA on the unit or building levels. In addition, the results illustrate the need for a flexible process method to provide effective ERA plans with multiple options. Economically, the results illustrate the importance of financial support from the state, as this would have positive consequences for the country's future economy.

The short-term consequences of ERAs were discussed, necessitating proactive actions from various beneficiaries, including the state, market, and community. These actions encompass financial support programs, updates to energy efficiency policies, incentives for energy efficiency upgrades, mandates for energy efficiency standards in the market, and initiatives to enhance the community awareness of energy efficiency. Simultaneously, the long-term consequences of ERAs were explored, specifically focusing on increasing energy efficiency awareness and its expected impact on energy savings in residential buildings. Furthermore, the chapter delved into the benefits of ERA implementation for decision-makers involved in existing residential buildings in Jeddah.

The chapter emphasized the urgency for energy retrofit plans in existing residential buildings, including the need for immediate action to achieve a stronger economy and a healthier environment. This highlights the importance of ongoing evaluation and assessment to design appropriate energy efficiency action plans. By prioritizing continuous improvement, decision-makers can effectively navigate the challenges associated with energy retrofit actions and maximize their positive impacts on residential buildings.

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7 Conclusions

7.1 Introduction

This study aimed to explore the potential benefits of energy retrofitting applications (ERAs) for mid-rise residential buildings in the Kingdom of Saudi Arabia (KSA) and guide decision-makers on implementing policy actions for ERAs. The research was driven by the urgent need to reduce the energy demand of residential buildings in the KSA, as they account for around 50% of the country's total electricity consumption. This is crucial to prevent an oil crisis by 2030 and to achieve the net-zero emission target by 2060.

Implementing ERAs in residential buildings is crucial, given the recent introduction of energy efficiency measures that affect residents' monthly electricity bills. To successfully promote ERAs in the KSA, decision-makers must establish action policies and supportive incentives that cater to the residents' needs for bill reduction and align with the state and market context. In this thesis, a typical ERA method was proposed that can provide significant savings in energy and costs for a study model, which decision-makers can use to promote ERAs.

Chapter 7 serves as the conclusion of this thesis. The chapter revisits the research question and sub-questions and summarizes the main findings of each chapter. The chapter outlines the method used in the conclusions chapter and summarizes the sub-question outcomes to answer the main research question. Recommendations for ERAs in the KSA context are presented, followed by recommendations for further research development. The thesis ends by illustrating different recommendations.

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7.2 Outcomes

A Research Question

What are the most energy-efficient and cost-effective retrofit schemes for upgrading the building envelopes of existing residential buildings in Jeddah, Saudi Arabia, and how can the findings guide architects and decision-makers in implementing energy-saving measures for residential buildings?

The primary research question can be deconstructed into several sub-questions pertaining to the existence of problems, energy retrofitting opportunities, energy-saving validation, cost–benefit analysis, and ERA consequences. The approach's efficacy and knowledge have been established by elaborating on these terms, as elucidated in the research sub-questions, which are subsequently answered.

B Research sub-questions

B1 – What are the primary factors responsible for the high energy consumption in residential buildings in Jeddah, Saudi Arabia?

In order to develop an effective strategy for energy upgrading, it is crucial to identify the primary factors responsible for high energy consumption. Therefore, the first step involves problem identification and determination of underlying causes.

In this study, a survey was conducted on residential buildings in Jeddah city, yielding important information regarding three key factors contributing to high energy consumption: building energy performance, user activities, and electricity tariffs. The results indicate that most residential buildings lack thermal insulation, which has led to suboptimal thermal comfort for building occupants. Consequently, users have to operate air conditioning systems longer to achieve the desired thermal conditions. Furthermore, the recent increase in electricity tariffs and the introduction of additional VAT have harmed user satisfaction with electricity pricing.

These findings highlight an urgent need for the energy upgrading of existing residential buildings to improve user satisfaction and address the challenge of increasing electricity tariffs. Implementing energy upgrade solutions offers a promising opportunity to meet user needs and enhance the energy performance of residential buildings.

B2 – What potential energy retrofitting options can be employed to enhance the energy efficiency of residential buildings in Jeddah, Saudi Arabia?

In order to propose successful approaches for energy retrofitting applications, defining appropriate parameters is crucial. In this study, a framework was established to identify relevant parameters and create a solid foundation for proposed energy upgrade strategies. The Jeddah context was discussed at various levels, including a background review, an overview of the existing residential building stock, design parameters, and key performance indicators (KPIs). In addition, the review of background information presented Saudi Arabia's cultural background and cost of living changes, followed by a review of applicable energy retrofitting strategies. The study addressed the difficulties associated with energy performance, the climate of Jeddah, and the residential building stock. Further, design parameters and key performance indicators (KPIs) were presented. Hence, potential energy-upgrading measures for the targeted construction method are presented in terms of individual improvements. The framework established specific criteria for identifying residential building energy upgrade options in Jeddah, requiring further investigation into energy savings and cost-effectiveness.

B3 – To what extent can the implementation of energy-retrofitting scenarios on building envelopes enhance the energy efficiency of mid-rise residential buildings in Jeddah, Saudi Arabia?

Adopting energy retrofitting strategies for building envelopes is crucial in reducing energy consumption and mitigating the environmental impact of buildings. Mid-rise residential buildings in Jeddah, Saudi Arabia, experience significant energy demand for cooling due to the hot and dry climate throughout the year, resulting in 6587 cooling degree days (CDDs). To significantly improve the energy efficiency of these buildings, implementing energy retrofitting scenarios that enhance thermal comfort and reduce energy consumption can reduce the total greenhouse gas emissions in the KSA.

Various energy retrofitting strategies can be employed, such as upgrading insulation (building envelope), using energy-efficient glazing, improving air sealants, and enhancing the efficiency of AC systems. These strategies can reduce the building's heat gain, improve indoor thermal comfort, and decrease reliance on mechanical cooling systems. The study focused on primary interventions that are possible for different budget levels. The effectiveness of these retrofitting scenarios can be evaluated through energy modeling and monitoring of energy consumption before and after retrofitting. This would allow the identification of potential energy savings and assessment of the economic feasibility of the retrofitting project. It is important to note that the existing building/unit energy performance levels and air change per hour (ACH) rate are significant factors to consider before conducting simulation scenarios to demonstrate their impact on the proposed model. The digital simulation results reveal that energy retrofitting of building envelopes can reduce energy consumption by up to 65%, leading to significant cost savings for building owners and occupants in the long-run. The unit position, orientation, and ACH rate level are significant in selecting scenarios and obtaining simulation results.

In conclusion, energy retrofitting scenarios for building envelopes can significantly enhance the energy efficiency of mid-rise residential buildings in Jeddah, Saudi Arabia. The evaluated scenarios can reduce energy consumption by 25% up to 65%, improving thermal comfort by lowering the infiltration rate to 4 ACH50 and mitigating the environmental impact of buildings. Further research and analysis are necessary to evaluate the effectiveness and feasibility of different energy retrofitting strategies in the specific context of Jeddah.

B4 – How beneficial is it to implement energy retrofitting applications (ERAs) for existing residential buildings, and which alternative approaches offer the most cost-effective solutions?

The cost-effectiveness of ERAs poses the most significant challenge in the KSA, where their introduction and implementation are relatively new. However, with the increasing electricity tariffs, ERAs would allow users to reduce their monthly bills. While the basic calculation of energy retrofitting is valuable, understanding the overall perspective of ERAs within the KSA context necessitates the incorporation of additional variables, such as oil selling, in the cost analysis equation.

The thesis assessed the energy savings of proposed scenarios and investigated the investment cost and payback measures to compare proposed scenarios in terms of payback periods. The investment cost significantly influences the payback period option, where a higher interest rate results in longer payback periods and lower applicability chances. Therefore, implementing ERAs is economically beneficial for users and the state, particularly when considering oil-selling opportunities from electricity savings is the most cost-effective solution.

B5 – What is the impact of ERAs on residential buildings in the KSA in terms of their environmental, economic, and social implications?

Understanding the impact of ERAs at the city level is crucial for decision-makers to design and implement effective policies for residential buildings in the KSA. The thesis suggested the impacts of ERA on a building level by identifying short-term and long-term consequences for three stakeholders: state, market, and community.

To achieve the goal of net-zero emissions buildings, the state would need to implement effective action policies and supporting programs. This would require the market to adhere to specific standards and improve the quality of energy products, leading to more job opportunities. In addition, building users stand to benefit from ERAs, as they can improve the energy performance, thermal comfort, property value, and lifespan, and ultimately reduce monthly electricity bills.

In conclusion, implementing ERAs in existing residential buildings is an urgent and high-priority measure to ensure energy-efficient residential buildings.

The sub-questions answer the research question by providing a contextual framework for decision-makers seeking to enhance the energy efficiency of residential envelopes using the energy retrofitting application approach. This method encompasses four categories of information that can facilitate the development of effective energy upgrade strategies. Initially, the approach identifies the leading causes and building envelope components requiring attention in upgrading existing residential buildings, presenting potential energy retrofitting interventions. Subsequently, it validates diverse energy retrofitting interventions regarding their energy savings potential by estimating the simulated energy demand reduction that can be attained after implementing each scenario. Furthermore, the approach analyses the cost benefits of each scenario, delineating diverse alternatives that benefit different beneficiaries. Lastly, the approach assesses the short- and long-term consequences of specific case study models, facilitating the decision to implement energy retrofitting applications in existing residential buildings.

Consequently, the ERA approach calculations offer an estimate of the energy savings potential that translates into a reduction in electricity bills. Furthermore, the ERA approach aids decision-makers by presenting available options and emphasizing the crucial consequences of the ERA application process. All of the information ERAs provide can benefit decision-makers involved in the ERA process. The approach primarily targets architects and decision-makers responsible for developing and implementing the energy upgrade design. However, users, owners, and other stakeholders can also utilize the information.

C Guidelines for Architects and Designers

The imperative for upgrading energy efficiency in residential buildings is particularly salient for the Kingdom of Saudi Arabia (KSA) as it strives to meet its 2060 net-zero emissions target. Within the KSA landscape, the application of energy retrofitting necessitates well-defined guidelines. These guidelines would enable architects and designers to implement energy-saving measures effectively while maintaining cost-efficiency. Additionally, such guidelines could serve as a reference for decision-makers, be they national or local authorities, in the allocation of financial resources to support energy retrofitting initiatives in residential buildings. The research presented in this thesis culminates in the establishment of the following guidelines for energy retrofitting application in residential buildings in KSA:

1 **User and Owner Participation:**

- Involve building users and owners in the design process to understand and integrate their needs into the final design.
- Evaluate the investor's financial status (user or owner), including income, energy expenses, and total monthly savings.
- Assess user behavior, such as monthly activities and air conditioner usage per room.
- Evaluate user knowledge of energy efficiency, including awareness of electricity consumption, appliance efficiency, and the broader impacts of energy consumption.

2 **Design Framework Development:**

Designers must establish a comprehensive energy retrofit application framework, aligning specific parameters with user needs and state requirements to achieve mutually beneficial outcomes. The framework should encompass:

- A background review including cultural context, current best practices, appropriate energy retrofitting strategies, current energy performance, and climate challenges.
- An overview of building stock, focusing on typology, prevalent construction methods, and available materials.
- Identification of Key Performance Indicators (KPIs).
- Recommendations for generic interventions.

3 **Energy Simulation Requirements:**

Proper energy simulation demands specific preparatory information to derive optimum solutions, including:

- Design parameters and energy benchmarks.
- A comprehensive case study description detailing building location, user profiles, and ownership structures.
- Monthly electricity bills spanning one year.
- For enhanced accuracy, this thesis advocates for monitoring ACH50 and electricity consumption.

4 **Cost Analysis:**

- Conducting thorough cost analysis is imperative to identifying viable solutions, which includes calculating renovation costs (current energy costs, intervention costs, and maintenance) and comparing selected scenarios.
- The core indicator of cost analysis is determining the payback period for each scenario, which hinges on the source of investment and the selected payback measures.
- Select suitable cases after comparing varied alternatives, each yielding different outcomes.

5 **Evaluation of Consequences:**

- Explicitly state the ramifications of energy application and undertake requisite calculations.
- Examine both short-term and long-term consequences of the selected cases, discussing their implications on the state, market, and community at large.

These guidelines aim to provide a foundational structure for architects and designers, ensuring the effective implementation of energy retrofitting applications in residential buildings within the Kingdom of Saudi Arabia, by integrating user needs, state requirements, and environmental considerations.

TOC

7.3 Future Work

This study focused on a specific climate region that allowed for significant results. However, additional research is needed for other climates in the KSA using the same method for a comprehensive approach, as these climates may affect the proposed solutions' applicability. Conducting a multi-application of the method for other climates in the KSA would extend the use of the proposed method. For instance, it is essential to consider the potential variation in climatic conditions across different regions in the KSA when implementing energy retrofitting applications.

The thesis included typical user activities that would vary in reality from one unit to another, where additional considerations would affect the simulation results. Expanding the simulation for other activity scenarios would result in different findings that could be used to create a database for future applications. Additionally, future development needs to consider increasing the number of cases to understand the common behaviors of building energy performance. For example, exploring the influence of different occupancy patterns and user behaviors on energy consumption can help develop more accurate simulations.

The electricity consumption of space cooling for existing buildings was used to indicate the energy performance level in the building, while other electricity consumption, such as water heating, electric devices, and lighting, was disregarded. Further development of ERAs that requires these detailed calculations to arrive at more effective solutions is essential. Therefore, future research can focus on developing more comprehensive energy models that account for all aspects of building energy consumption.

The thesis focused on limited energy retrofitting strategies available in the market, which are low cost and easy to implement. Further developments in respect of other strategies that could allow for net-zero buildings, such as using renewable energy, are necessary, while also considering the cost–benefit analysis.

Digital simulation was used in this study to define and understand building energy performance. However, future work monitoring existing buildings in the KSA is essential to verify some uncertainties in the simulation process, as insufficient research has been performed in the KSA context. In addition, monitoring the building after the ERA is essential to ensure accurate results or develop better approaches. Hence, future research could focus on conducting post-occupancy evaluations to verify the actual performance of the retrofitted buildings.

The thesis introduced the decision approach in a more general form, while future development is needed to invite specialized members/teams to discuss the possible decision approach that depends on political approaches. Therefore, more research is needed to understand the complexities of decision-making processes and identify effective strategies for engaging relevant stakeholders.

Additionally, an alternate scenario was explored to assess the feasibility of further upgrades, involving the addition of supplementary insulation. This amendment led to incremental energy savings ranging between 3.5% to 6.5%. However, this enhancement incurred substantial costs, escalating the overall expenditure by more than 65%. This surge in cost undermined the cost-effectiveness of this scenario, prolonging the payback periods from 5 to 13 years.

Notwithstanding, attaining more efficacious scenarios to achieve a zero-net-energy building may be plausible, albeit with additional expenditures. Thus, future research endeavors should delve deeper into the possibilities of achieving zero-net-energy buildings. Emphasis should be on enhancing the efficiency of various building components, such as window attributes (including frame, glazing, and shading), wall U-values, and roof U-values, to optimize energy performance in existing buildings.

The potential advancements in these areas can significantly impact the energy efficiency of buildings, contributing to the development of more sustainable and environmentally friendly living spaces in the Kingdom of Saudi Arabia. The investigation into more intricate and comprehensive modifications offers a path to reconciling the pursuit of energy efficiency with financial feasibility, providing a blueprint for future energy retrofitting projects.

Finally, the thesis provided significant knowledge to promote energy efficiency. Future work needs to spread this knowledge to the public through different activities, such as media, education, and, more importantly, representative projects. This can include developing public outreach programs and engaging with local communities to promote energy-efficient behavior and increase awareness about the benefits of energy retrofitting applications.

7.4 Recommendations

The thesis investigated the energy retrofitting application in terms of energy efficiency, cost benefits, and the decision-making impact on ERAs. Different issues were addressed for implementing ERAs in the Saudi context, taking Jeddah as a case study. The suggestions below are proposed to ease the execution of ERAs on residential buildings.

1 **Establish a specialized association for energy retrofitting applications within the SEEC to improve the energy efficiency of existing buildings and connect with international research centers.**

- The association should include energy efficiency experts, engineers, architects, and other relevant professionals.
- The association should focus on developing and implementing energy retrofitting policies and standards, as well as disseminating best practices (see Chapters 2-5).
- The association should collaborate with international research centers to exchange knowledge and expertise.
- The energy consumption database of existing buildings should include information on building types, ages, materials, and other relevant factors to help identify adequate energy retrofitting solutions.
- Digital simulations should be used to model the energy performance of buildings before and after energy retrofitting to assess the effectiveness of different solutions.
- Develop a monitoring and evaluation system to track the impact of energy retrofitting projects on energy consumption, comfort levels, and other relevant metrics (see Chapter 4).
- Residents should be involved in developing energy retrofitting methods to ensure they are culturally appropriate and socially acceptable.
- Develop guidelines and standards for selecting energy-efficient building materials and technologies to ensure they are effective, safe, and appropriate for local contexts (use Chapter 2 and expand it to provide more detail).
- Energy efficiency labeling for buildings should be developed to inform consumers about the energy performance of buildings and encourage energy efficiency improvements (see Chapters 4 and 5).

2 **Enforce energy efficiency standards for existing buildings with financial support programs and initiatives.**

- Financial support programs should be developed to help building owners and residents finance energy retrofitting projects (see Chapters 5 and 6).
- Develop public–private partnerships to finance energy retrofitting projects, leveraging private investment to achieve energy efficiency goals.
- Develop performance-based incentives for building owners and residents to encourage energy efficiency improvements and retrofitting projects.
- Existing energy efficiency programs should be evaluated and improved to ensure their effectiveness.
- Conduct regular energy audits of buildings to identify energy savings and retrofitting opportunities.
- Local updates to energy efficiency standards should be allowed to account for regional differences in building practices and climates (see Chapters 2-6).
- The local municipality will be vital in enforcing energy efficiency standards and promoting energy retrofitting.
- Quality standards for energy retrofitting should be developed to ensure that energy retrofitting projects meet high standards and effectively reduce energy consumption.
- Develop a certification system for energy efficiency experts and contractors to ensure they have the necessary skills and knowledge to effectively carry out energy retrofitting projects.
- Bureaucratic restrictions, such as excessive paperwork or delays in permitting, should be identified and addressed to help facilitate energy retrofitting projects.

3 **Disseminate energy efficiency.**

- Energy efficiency education should be integrated into all primary and higher education levels to raise awareness and promote behavior change.
- Additional energy efficiency courses should be offered for specialized subjects in the curriculum, such as engineering and architecture.
- The local municipality should organize public workshops and lectures to involve the community in energy efficiency initiatives.
- Develop a public outreach program to engage with the public and increase awareness of energy efficiency and retrofitting benefits.
- Supporting programs, such as incentives and subsidies, should be offered to encourage residents to adopt energy-efficient practices.
- Media campaigns targeting different age categories should be developed to raise awareness about energy efficiency and promote behavior change.
- Introduce actual exemplary projects per city, such as retrofitting a public

building or a residential complex, which should be implemented to demonstrate the effectiveness of energy retrofitting and encourage adoption. These projects should include before-and-after monitoring to demonstrate the impact on energy consumption and comfort levels.

- A three-dimensional representation of rooms can be created using physical models or virtual reality (VR) technology, effectively illustrating the differences in thermal comfort levels before and after energy retrofitting. This can be a valuable tool for demonstrating the effectiveness of energy retrofitting to building owners, residents, and policymakers.
- Develop pilot projects in different neighborhoods to test the effectiveness of energy retrofitting solutions in diverse contexts and building types.

4 **Conduct research and development on innovative energy-efficient technologies and sustainable building materials.**

- Investigate the potential use of cutting-edge building materials and technologies to enhance the energy efficiency of residential buildings in Saudi Arabia. Collaborate with local and international research centers to conduct research and experimental retrofitting projects across different country regions to refine and test new methods.
- Foster partnerships with local universities and research institutions to promote research on energy efficiency and energy retrofitting in residential buildings.
- Promote the integration of renewable energy sources in residential buildings for future applications.

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Appendices

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APP. A A Comparison of Thickness R-values and U-values with various scenarios

		Thickness (cm)	R-Values (m2·K/W)	U-Values (W/m^{2}K)		Thickness (cm)	R-Values (m2·K/W)	U-Values (W/m^{2}K)
Basic Existing Wall	Outdoor Cement Mortar	0.030	0.042	24.000	Outdoor Cement Mortar	0.030	0.042	24.000
	Cement block	0.200	0.205	4.880	Red Block	0.200	0.524	1.910
	Indoor Cement Mortar	0.020	0.028	36.000	Indoor Cement Mortar	0.020	0.028	36.000
	Total	**0.250**	**0.274**	**3.645**	**Total**	**0.250**	**0.593**	**1.686**
A. Scenarios Indoor interventions								
A.1 1 Indoor intervetuntions	Indoor Polystyrene	0.050	1.786	0.560	Indoor Polystyrene	0.050	1.786	0.560
	Total	**0.300**	**2.060**	**0.485**	**Total**	**0.300**	**2.379**	**0.420**
	Indoor Burkani	0.200	0.800	1.250	Indoor Burkani	0.200	0.800	1.250
	Total	**0.500**	**2.860**	**0.350**	**Total**	**0.500**	**3.179**	**0.315**
A.2 1 Indoor intervention	Indoor Polystyrene	0.075	2.679	0.373	Indoor Polystyrene	0.075	2.679	0.373
	Total	**0.325**	**2.953**	**0.339**	**Total**	**0.325**	**3.272**	**0.306**
A.3 1 Indoor interventions	Rockwool	0.050	1.389	0.720	Rockwool	0.050	1.389	0.720
	Total	**0.300**	**1.663**	**0.601**	**Total**	**0.300**	**1.982**	**0.505**
	Indoor Polystyrene	0.050	1.786	0.560	Indoor Polystyrene	0.050	1.786	0.560
	Total	**0.350**	**3.449**	**0.290**	**Total**	**0.350**	**3.768**	**0.265**
A.4 1 Indoor intervention	Rockwool	0.110	3.056	0.327	Rockwool	0.110	3.056	0.327
	Total	**0.360**	**3.330**	**0.300**	**Total**	**0.360**	**3.649**	**0.274**
A.5 2 Indoor interventions	Perlite con	0.100	1.233	0.811	Perlite con	0.100	1.233	0.811
	Total	**0.350**	**1.507**	**0.663**	**Total**	**0.350**	**1.826**	**0.548**
	Indoor Polystyrene	0.050	1.786	0.560	Indoor Polystyrene	0.050	1.786	0.560
	Total	**0.400**	**3.293**	**0.304**	**Total**	**0.400**	**3.612**	**0.277**

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		Thickness (cm)	R-Values (m2·K/W)	U-Values (W/m²K)		Thickness (cm)	R-Values (m2·K/W)	U-Values (W/m²K)
B. Scenarios (Outdoor interventions + Indoor interventions)								
B.1 1 outdoor intervention + 1 Indoor intervention	Outdoor EIFS (24)	0.045	1.505	0.664	Outdoor EIFS (24)	0.045	1.505	0.664
	Total	**0.295**	**1.779**	**0.562**	**Total**	**0.295**	**2.098**	**0.477**
	Indoor Polystyrene	0.050	1.786	0.560	Indoor Polystyrene	0.050	1.786	0.560
	Total	**0.345**	**3.565**	**0.280**	**Total**	**0.345**	**3.884**	**0.257**
B.2 1 outdoor intervention + 1 Indoor intervention	Outdoor EIFS (34.4)	0.035	1.452	0.689	Outdoor EIFS (34.4)	0.035	1.452	0.689
	Total	**0.285**	**1.726**	**0.579**	**Total**	**0.285**	**2.045**	**0.489**
	Indoor Polystyrene	0.050	1.786	0.560	Indoor Polystyrene	0.050	1.786	0.560
	Total	**0.335**	**3.512**	**0.285**	**Total**	**0.335**	**3.831**	**0.261**
B.3 1 outdoor intervention + 1 Indoor intervention	Outdoor EIFS (48)	0.035	1.515	0.660	Outdoor EIFS (48)	0.035	1.515	0.660
	Total	**0.285**	**1.790**	**0.559**	**Total**	**0.285**	**2.108**	**0.474**
	Indoor Polystyrene	0.050	1.786	0.560	Indoor Polystyrene	0.050	1.786	0.560
	Total	**0.335**	**3.575**	**0.280**	**Total**	**0.335**	**3.894**	**0.257**
B.4 1 outdoor intervention + 1 Indoor intervention	Outdoor EIFS (48)	0.035	1.515	0.660	Outdoor EIFS (48)	0.035	1.515	0.660
	Total	**0.285**	**1.790**	**0.559**	**Total**	**0.285**	**2.108**	**0.474**
	Indoor Polystyrene	0.050	1.786	0.560	Indoor Polystyrene	0.050	1.786	0.560
	Total	**0.335**	**3.575**	**0.280**	**Total**	**0.335**	**3.894**	**0.257**
B.5 1 Indoor intervention	Outdoor EIFS (48)	0.065	2.814	0.355	Outdoor EIFS (48)	0.065	2.814	0.355
	Total	**0.315**	**3.088**	**0.324**	**Total**	**0.315**	**4.203**	**0.238**

		Thickness (cm)	R-Values (m2·K/W)	U-Values (W/m^2K)		Thickness (cm)	R-Values (m2·K/W)	U-Values (W/m^2K)
Basic Existing Wall	Outdoor Cement Mortar	0.030	0.042	24.000	Outdoor Cement Mortar	0.030	0.042	24.000
	Burkani Block (2200)	0.200	0.800	1.250	Siporex (520)	0.200	1.282	0.780
	Indoor Cement Mortar	0.020	0.028	36.000	Indoor Cement Mortar	0.020	0.028	36.000
	Total	**0.250**	**0.869**	**1.150**	**Total**	**0.250**	**1.351**	**0.740**
A. Scenarios Indoor interventions								
A.1 2 Indoor interventions	Indoor Polystyrene	0.050	1.786	0.560	Indoor Polystyrene	0.050	1.786	0.560
	Total	0.300	2.655	0.377	Total	0.300	3.137	0.319
	Indoor Burkani	0.200	0.800	1.250	Indoor Burkani	0.200	0.800	1.250
	Total	**0.500**	**3.455**	**0.289**	**Total**	**0.500**	**3.937**	**0.254**
A.2 1 Indoor intervention	Indoor Polystyrene	0.075	2.679	0.373	Indoor Polystyrene	0.075	2.679	0.373
	Total	**0.325**	**3.548**	**0.282**	**Total**	**0.325**	**4.030**	**0.248**
A.3 2 Indoor interventions	Rockwool	0.050	1.389	0.720	Rockwool	0.050	1.389	0.720
	Total	**0.300**	**2.258**	**0.443**	**Total**	**0.300**	**2.740**	**0.365**
	Indoor Polystyrene	0.050	1.786	0.560	Indoor Polystyrene	0.050	1.786	0.560
	Total	**0.350**	**4.044**	**0.247**	**Total**	**0.350**	**4.526**	**0.221**
A.4 1 Indoor intervention	Rockwool	0.110	3.056	0.327	Rockwool	0.110	3.056	0.327
	Total	**0.360**	**3.925**	**0.255**	**Total**	**0.360**	**4.407**	**0.227**
A.5 2 Indoor interventions	Perlite con	0.100	1.233	0.811	Perlite con	0.100	1.233	0.811
	Total	**0.350**	**2.102**	**0.476**	**Total**	**0.350**	**2.584**	**0.387**
	Indoor Polystyrene	0.050	1.786	0.560	Indoor Polystyrene	0.050	1.786	0.560
	Total	**0.400**	**3.888**	**0.257**	**Total**	**0.400**	**4.370**	**0.229**

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		Thickness (cm)	R-Values (m2·K/W)	U-Values (W/m^{2}K)		Thickness (cm)	R-Values (m2·K/W)	U-Values (W/m^{2}K)
B. Scenarios (Outdoor interventions + Indoor interventions)								
B.1 1 outdoor intervention + 1 Indoor intervention	Outdoor EIFS (24)	0.045	1.505	0.664	Outdoor EIFS (24)	0.045	1.505	0.664
	Total	**0.295**	**2.374**	**0.421**	**Total**	**0.295**	**2.857**	**0.350**
	Indoor Polystyrene	0.050	1.786	0.560	Indoor Polystyrene	0.050	1.786	0.560
	Total	**0.345**	**4.160**	**0.240**	**Total**	**0.345**	**4.642**	**0.215**
B.2 1 outdoor intervention + 1 Indoor intervention	Outdoor EIFS (34.4)	0.035	1.452	0.689	Outdoor EIFS (34.4)	0.035	1.452	0.689
	Total	**0.285**	**2.321**	**0.431**	**Total**	**0.285**	**2.803**	**0.357**
	Indoor Polystyrene	0.050	1.786	0.560	Indoor Polystyrene	0.050	1.786	0.560
	Total	**0.335**	**4.107**	**0.243**	**Total**	**0.335**	**4.589**	**0.218**
B.3 1 outdoor intervention + 1 Indoor intervention	Outdoor EIFS (48)	0.035	1.515	0.660	Outdoor EIFS (48)	0.035	1.515	0.660
	Total	**0.285**	**2.385**	**0.419**	**Total**	**0.285**	**2.867**	**0.349**
	Indoor Polystyrene	0.050	1.786	0.560	Indoor Polystyrene	0.050	1.786	0.560
	Total	**0.335**	**4.170**	**0.240**	**Total**	**0.335**	**4.652**	**0.215**
B.4 1 outdoor intervention + 1 Indoor intervention	Outdoor EIFS (48)	0.035	1.515	0.660	Outdoor EIFS (48)	0.035	1.515	0.660
	Total	**0.285**	**2.385**	**0.419**	**Total**	**0.285**	**2.867**	**0.349**
	Indoor Polystyrene	0.050	1.786	0.560	Indoor Polystyrene	0.050	1.786	0.560
	Total	**0.335**	**4.170**	**0.240**	**Total**	**0.335**	**4.652**	**0.215**
B.5 1 outdoor intervention	Outdoor EIFS (48)	0.065	2.814	0.355	Outdoor EIFS (48)	0.065	2.814	0.355
	Total	**0.315**	**4.203**	**0.238**	**Total**	**0.315**	**4.203**	**0.238**

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APP. B Survey Form in English language

Residential Buildings: energy consumption and cost evaluation

- Recently, Saudi Arabia is investing heavily in renewable energy sources. Saudi Buildings consume over 75% of the total electricity produced in the country. The residential buildings account half of the buildings stock energy consumption.
- This study is part of an ongoing PhD that focusing on optimizing energy performance for residential buildings envelope in Saudi Arabia.
- The aim of the research is to enhance the residential buildings energy performance using Jeddah as a case study to help the design strategies decisions on building envelope.
- Your inputs in this survey is to show the current developments effects on utilities bills and the building users in two levels: monthly cost then users behaviors on energy consumption .
- This survey results will help the building designers for better buildings energy performance.
- This survey will take approximately 7-10 minutes.
- This survey is confidential and no name or identification is needed you (anonymous identification)

Please if you have any question send me an email to: afelimban@kau.edu.sa or a.a.m.felimban@tudelft.nl Thank you in advance Ahmed Felimban PhD Candidate

Participant information

0 – Are you a resident in Jeddah? *(Mark only one oval)*

☐ Yes ☐ No *(Skip to question 29)*

1 – How long have you been as a resident in Jeddah? *(Mark only one oval)*

☐ Less than a year ☐ 1-5 years ☐ 6-10 years ☐ more than 10 years

2 – What is your residency status? *(Mark only one oval)*

☐ Saudi Citizen ☐ Non Saudi resident

3 – What is your gender? *(Mark only one oval)*

☐ Male ☐ Female

4 – What is your social status? *(Mark only one oval)*

☐ Single ☐ Married ☐ Single mother\father

5 – What is your age? *(Mark only one oval)*

☐ Less than 20 ☐ 20-34 ☐ 35-49 ☐ 50-64 ☐ over 65

6 – What is your job? *(Mark only one oval)*

☐ Governmental employee ☐ Private Employee ☐ Private Business ☐ Unemployed

☐ Other: ____________________

7 – What is your Education Level? *(Mark only one oval)*

☐ Illiterate, Unlettered ☐ General Education (High School) and lower

☐ Associate degree (Community college or technical college) ☐ Undergraduate (Bachelor’s)

☐ Master’s ☐ Doctoral

8 – How many members of your family including you?

9 – In which range your Monthly income in Saudi Riyals? *(Mark only one oval)*

☐ 0-4,999 ☐ 5,000-9,999 ☐ 10,000-14,999 ☐ 15,000-19,999 ☐ 20,000-24,999 ☐ 25,000-29,999 ☐ 30,000 and more

10 – Your Monthly income in Saudi Riyals specifically?

Information of Your housing

11 – What type of housing you live in? *(Mark only one oval)*

☐ Apartment ☐ Villa ☐ Other:

12 – How many rooms are in your housing?

____________ *(English Number)*

13 – What is your house total area in square meters?

____________ *(English Number)*

14 – How much do you pay in monthly average for utilities(electricity- water-sewage-gas) in Saudi Riyals after 2018 changes?

____________ *(English Number)*

15 – What is your ownership status of the housing you live in? *(Mark only one oval)*

☐ Renting ☐ Owner *(Skip to question 18)*

☐ Job granted *(Skip to question 18)* ☐ Government granted *(Skip to question 18)*

☐ Other: ____________________

16 – How much is your yearly rent in Saudi Riyal?

____________ *(English Number)*

** Indicates required question*

Energy consumption and energy cost

17 – Which type of Air-conditioning are you using in your House? *(Mark only one oval)*

			
☐ Central Air-conditioning system	☐ Split Units Air-conditioning	☐ Window Air-conditioning	☐ Split Units Air-conditioning and Window Air-conditioning

☐ None

18 – How many AC units used in each space in total? *(Mark only one oval per row).*

____________ *(English Number)*

	1	2	3	4	5	6	7
Bedroom	☐	☐	☐	☐	☐	☐	☐
Kitchen	☐	☐	☐	☐	☐	☐	☐
Living room	☐	☐	☐	☐	☐	☐	☐
Guest room	☐	☐	☐	☐	☐	☐	☐

19 – How long your average daily use in each indoor space of the AC during weekdays in the summer season? *(Mark only one oval per row).*

	less than 1 hour	1-5 hours	6-10 hours	11-15 hours	16-20 hours	all-day hours
Bedroom	☐	☐	☐	☐	☐	☐
Kitchen	☐	☐	☐	☐	☐	☐
Living room	☐	☐	☐	☐	☐	☐
Guest room	☐	☐	☐	☐	☐	☐

20 – What type of light do you use? *(Check all that apply).*

			
☐ Halogen	☐ Fluorescent	☐ Vapor Lamps	☐ Light Emitting Diodes (LEDs)

☐ Other:

21 – How much did you pay for your electricity bill before 2018? (Monthly Average)

____________ *(English Number)*

22 – How much do you pay for your Electricity bill after 2018 tariffs changes?(Monthly Average)

____________ *(English Number)*

23 – How much do you pay for your water and sewage bill after 2018 tariffs changes? (Monthly Average)

____________ *(English Number)*

** Indicates required question*

24 – What is your average monthly consumption Per kilowatts?

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Bill Details

Subscription No.	22011737009441
Meter No	1456881
Ampere Capacity	60.00
Current Reading	150564
Previous Reading	147179
Coefficient	1.00000
Consumption Quant...	3385
Consumption Total	3385
Number Of Days	30
Tariff Type	سكني
Consumption Value	609.30
Meter Service	10.00
VAT 5%	30.97
Bill Amount	650.27
Previous Balance	657.26
Creditor Balance	.00
VAT Registration Nu...	300000361310003
Area No	2201-15 J01 - 17303 0000959

____________ *(English Number)*

the picture indicate where do you find it https://myservices.se.com.sa/sap/bc/ui5_ui5/sap/zumcui5_mobile/index.html#/L ogon

25 – Is your building insulated and meet the standard U-value requirements? ***(Mark only one oval)***

☐ Yes ☐ No ☐ I have No idea

User Satisfaction

26 – How are you satisfied with the following choices? * ***(Mark only one oval per row).***

	Strongly satisfied	satisfied	Natural	unsatisfied	Strongly unsatisfied
Room size	☐	☐	☐	☐	☐
Water and sewage services	☐	☐	☐	☐	☐
Water and sewage Prices	☐	☐	☐	☐	☐
Electricity services	☐	☐	☐	☐	☐
Electricity prices	☐	☐	☐	☐	☐
Daylight	☐	☐	☐	☐	☐
Thermal comfort	☐	☐	☐	☐	☐
Window ratio to room size	☐	☐	☐	☐	☐
Outside Noise	☐	☐	☐	☐	☐

27 – What is your average indoor preference temperature degree in Celsius ? ***(Mark only one oval)***

☐ Below 19 ☐ 19-21 ☐ 22-24 ☐ 25-27

Thank you for your participation

** Indicates required question*

Suggestions

Please indicate any ideas can help enhancing the indoor comfort

____

____

____

____

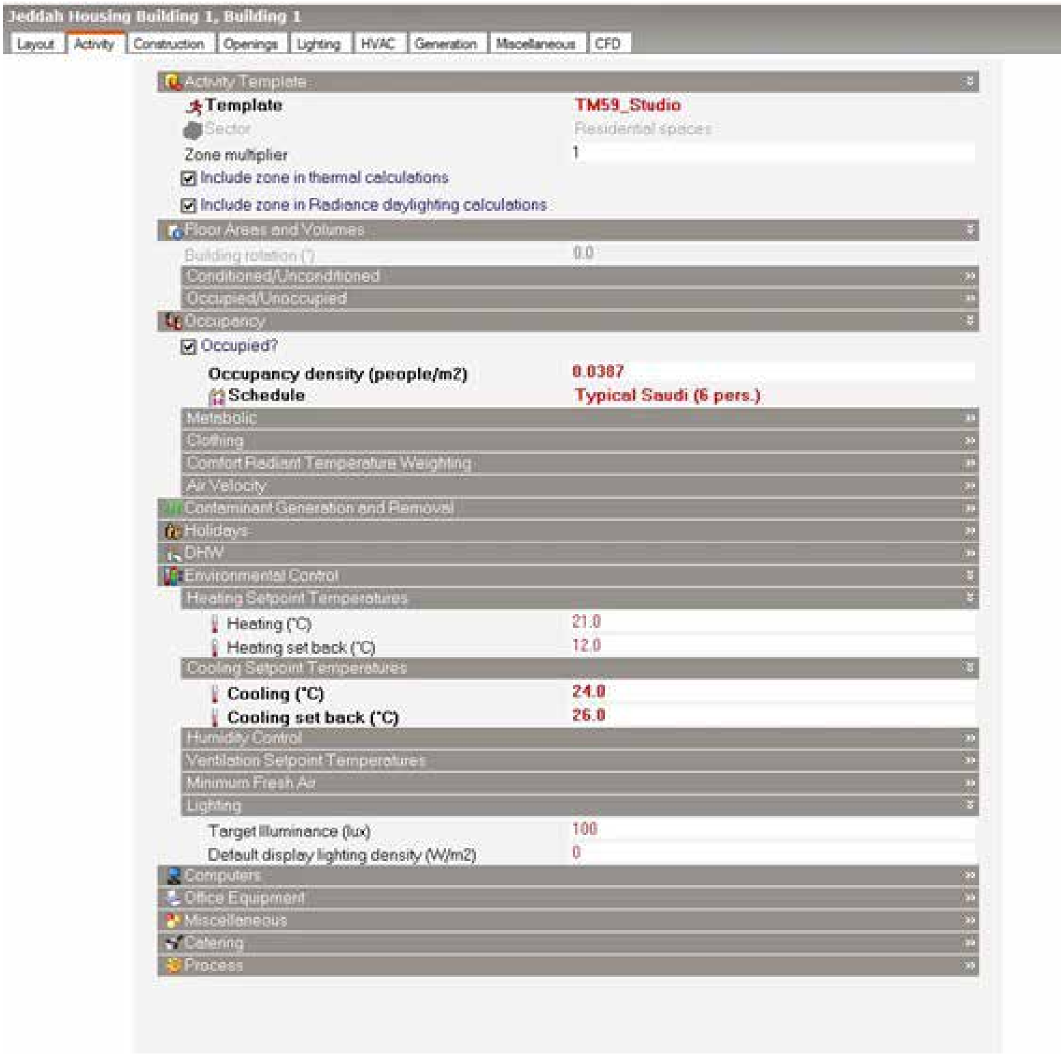
____

____

If you would like to be contacted with further detailed survey or interview please fill your email address

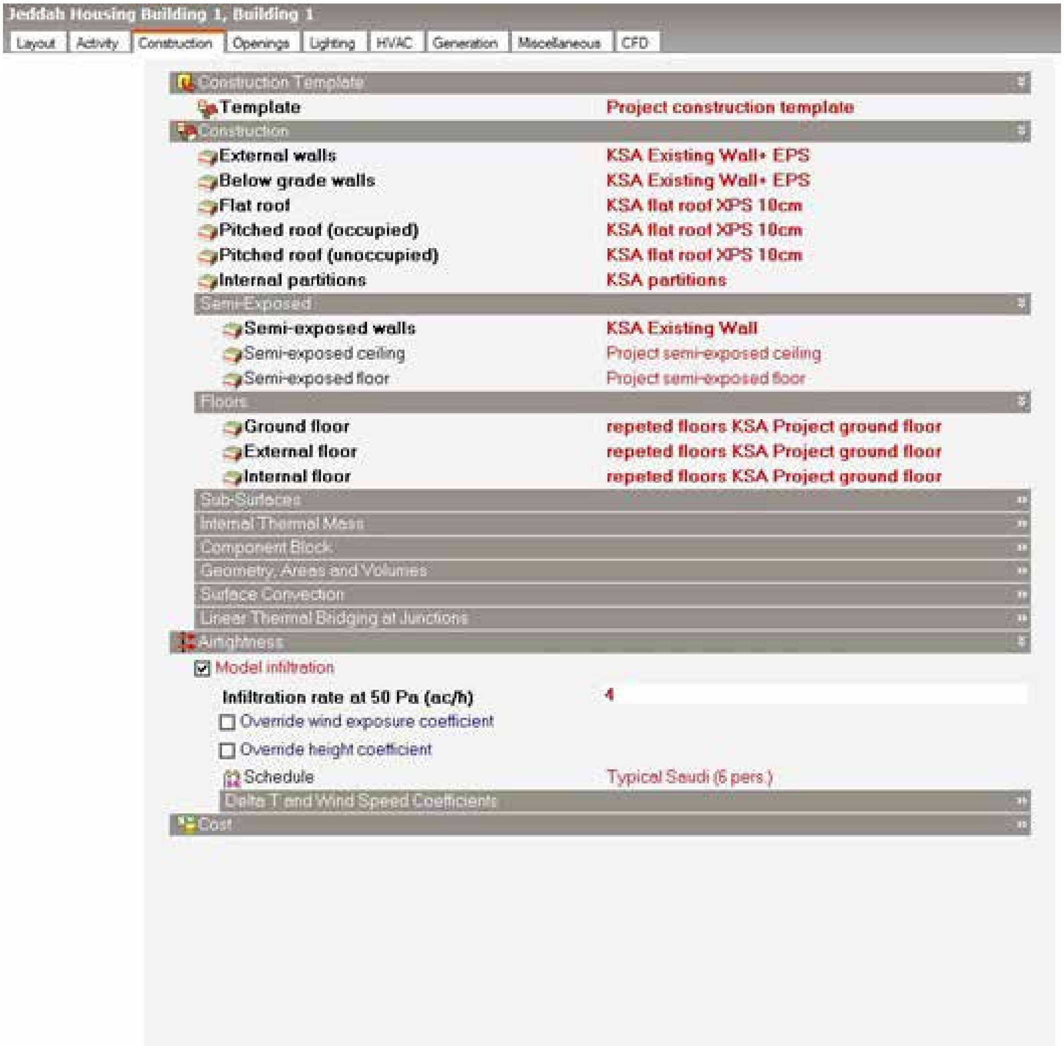
______________________________ *(Email Address)*

APP. C Design Builder Input



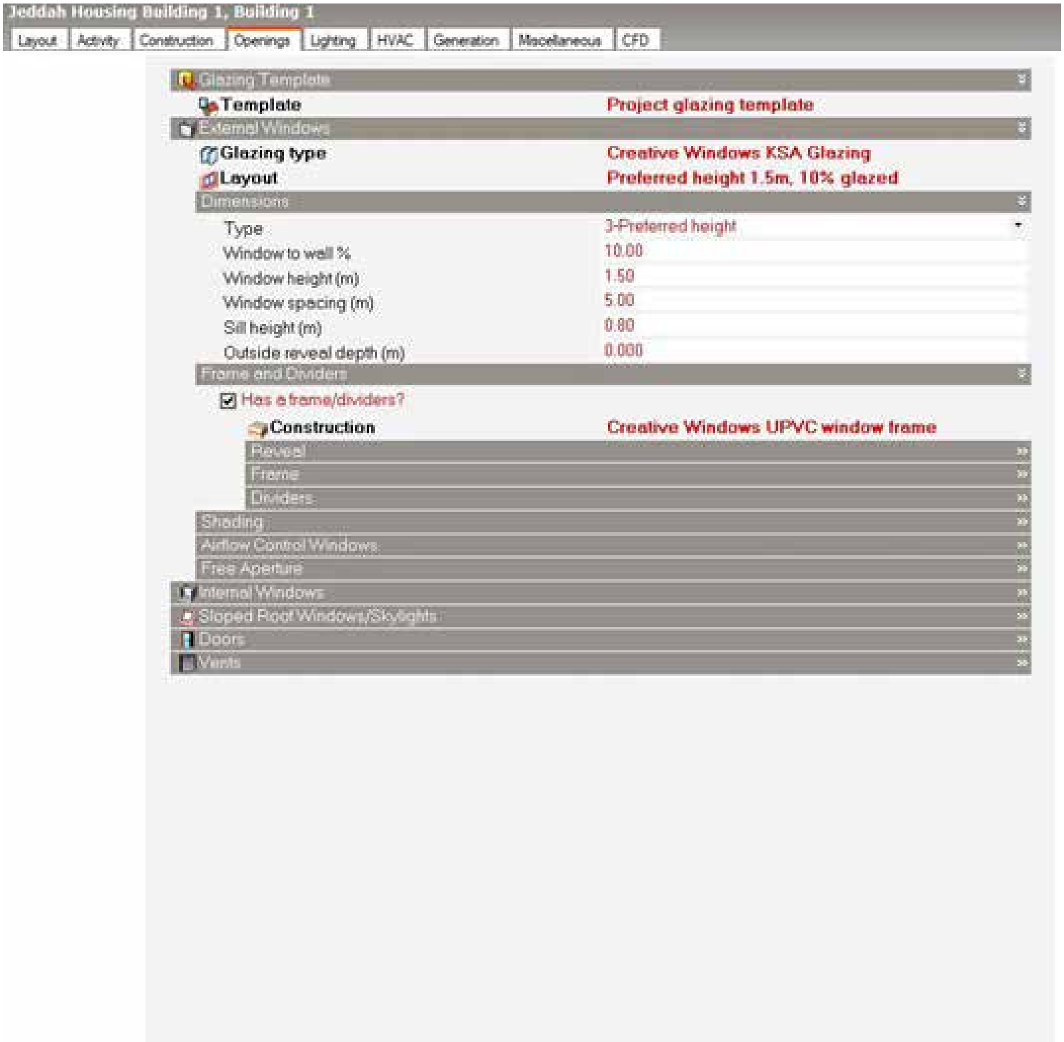
Jeddah Housing Building 1, Building 1

Activity Template	
Template	TM59_Studio
Sector	Residential spaces
Zone multiplier	1
☑ Include zone in thermal calculations	
☑ Include zone in Radiance daylighting calculations	
Floor Areas and Volumes	
Building rotation (°)	0.0
Conditioned/Unconditioned	
Occupied/Unoccupied	
Occupancy	
☑ Occupied?	
Occupancy density (people/m2)	0.0387
Schedule	Typical Saudi (6 pers.)
Metabolic	
Clothing	
Comfort Radiant Temperature Weighting	
Air Velocity	
Contaminant Generation and Removal	
Holidays	
DHW	
Environmental Control	
Heating Setpoint Temperatures	
Heating (°C)	21.0
Heating set back (°C)	12.0
Cooling Setpoint Temperatures	
Cooling (°C)	24.0
Cooling set back (°C)	26.0
Humidity Control	
Ventilation Setpoint Temperatures	
Minimum Fresh Air	
Lighting	
Target Illuminance (lux)	100
Default display lighting density (W/m2)	0
Computers	
Office Equipment	
Miscellaneous	
Catering	
Process	



Jeddah Housing Building 1, Building 1

Construction Template	
Template	Project construction template
Construction	
External walls	KSA Existing Wall+ EPS
Below grade walls	KSA Existing Wall+ EPS
Flat roof	KSA flat roof XPS 10cm
Pitched roof (occupied)	KSA flat roof XPS 10cm
Pitched roof (unoccupied)	KSA flat roof XPS 10cm
Internal partitions	KSA partitions
Semi-Exposed	
Semi-exposed walls	KSA Existing Wall
Semi-exposed ceiling	Project semi-exposed ceiling
Semi-exposed floor	Project semi-exposed floor
Floors	
Ground floor	repeted floors KSA Project ground floor
External floor	repeted floors KSA Project ground floor
Internal floor	repeted floors KSA Project ground floor
Sub-Surfaces	
Internal Thermal Mass	
Component Block	
Geometry, Areas and Volumes	
Surface Convection	
Linear Thermal Bridging at Junctions	
Airtightness	
☑ Model infiltration	
Infiltration rate at 50 Pa (ac/h)	4
☐ Override wind exposure coefficient	
☐ Override height coefficient	
Schedule	Typical Saudi (6 pers.)
Delta T and Wind Speed Coefficients	
Cost	



Template: Project glazing template

Glazing type: Creative Windows KSA Glazing

Layout: Preferred height 1.5m, 10% glazed

Type	3-Preferred height
Window to wall %	10.00
Window height (m)	1.50
Window spacing (m)	5.00
Sill height (m)	0.80
Outside reveal depth (m)	0.000

☑ Has a frame/dividers?

Construction: Creative Windows UPVC window frame

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Curriculum vitae

Ahmed Felimban

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1985	Born in Jeddah , KSA
2003-2008	Bachelor's Degree in Islamic Architecture (Second Honor) Faculty of Engineering and Islamic Architecture Umm AlQura University, Makkah, Saudi Arabia
2004-2007	Supervisor Leader's pilgrim's non-Arab African Countries Company, Makkah, Saudi Arabia
2009-2013	Teaching Assistant, King Abdul-Aziz University, Jeddah, Saudi Arabia
2012-2013	Master's Degree 2013 in Architecture (Dean's list Fall 2012, Winter and Spring 2013), NewSchool of Architecture and Design College , San Diego, California, United States
2013-Present	Lecturer, Architecture and Planning Fuclty, King Abdul-Aziz University, Jeddah, Saudi Arabia
2018-Present	PhD. Researcher, Architectural Facades & Products (AF&P) Research Group, Faculty of Architecture, TU Delft, Delft, The Netherlands.

Publications

Journal paper

A. Felimban, A. Prieto, U. Knaack, T. Klein, and Y. Qaffas, “Assessment of current energy consumption in residential buildings in Jeddah, Saudi Arabia,” *Buildings*, vol. 9, no. 7, p. 163, Jul. 2019, doi: 10.3390/buildings9070163.

A. Felimban, U. Knaack, and T. Konstantinou, “Evaluating Savings Potentials Using Energy Retrofitting Measures for a Residential Building in Jeddah, KSA,” Buildings, vol. 13, no. 7, p. 1645, Jun. 2023, doi: 10.3390/buildings13071645.

Conference paper

Felimban, A. , Prieto, A. , Knaack, U. , Klein, T. (2020). “Energy Retrofitting Application Research to Achieve Energy Efficiency in Hot-Arid Climates in Residential Buildings: A Case Study of Saudi Arabia”. World Academy of Science, Engineering and Technology, Open Science Index 163, International Journal of Architectural and Environmental Engineering, 14 (7), 185 - 188.

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24#02

Towards Energy-Efficient Residential Buildings In Jeddah, Saudi Arabia

Exploring Energy Retrofitting Options And Assessing Their Feasibility

Ahmed Felimban

The thesis explores energy retrofitting options for enhancing the energy efficiency of residential buildings in Jeddah, Saudi Arabia. It identifies and validates cost-effective energy retrofit schemes that have the potential for energy savings. The thesis also assesses the feasibility of energy retrofitting scenarios for building envelopes and their impact on reducing energy consumption, improving thermal comfort, and mitigating the environmental impact of buildings. The results of this research can guide architects and decision-makers on energy-saving measures for residential buildings in Saudi Arabia, with Jeddah serving as a representative case study.

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