

Parametric Analysis and Life Cycle Cost Assessment for Optimizing PCM Application in Exterior Walls in the Kingdom of Saudi Arabia

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Abstract

The Kingdom of Saudi Arabia (KSA) aims to reduce CO₂ emissions and mitigate its environmental impact as part of Vision 2030. The building sector has high energy consumption, particularly due to elevated cooling demands, which make up 70% of residential energy use. This is largely caused by uninsulated thermal mass and subsidized electricity rates. In addition, Vision 2030's housing projects and labor shortage necessitate alternatives to current housing standards. Modular housing offers a solution to the labor shortage, but its success depends on lighter materials. This study proposes replacing thermal mass with PCM in modular housing and, investigates this using EnergyPlus simulations. The research investigated the optimal placement and thickness of PCM to maximize its thermal performance in SIPs. PCM application reduced the model total site energy by 12.9% to 13.7% with a thickness of 0.5–2.0 cm and significantly reduced the HVAC energy consumption by 37% to 39%. In this study, we developed LCCA models to assess the cost-effectiveness of PCM by establishing a price range per square foot that aligns with the energy savings that are usable in the KSA. This study also identified the maximum PCM production cost based on the LCCA analysis to ensure its investment use in KSA's construction industry.

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General Audience Abstract

KSA's Vision 2030 aims to reduce CO₂ emissions and minimize environmental impact. The building sector brought researchers attention since the energy used in the residential type accounts for 70% of the energy for cooling. The cooling demands it because of the lack of proper insulation in buildings and the low electricity rate. The country aims under Vision 2030 to advance its housing projects and faces a labor shortage. The modular housing proposed in this situation represents a promising solution to KSA. However, modular homes need to be built with lighter materials, and this study explores the potential of replacing traditional heavy building materials with PCM in modular homes. PCM helps control indoor temperatures by absorbing and releasing heat, improving energy efficiency. The research used the energy simulation method to investigate and determine the optimal placement and thickness of PCM within SIPs. PCM utilization reduced the model total site energy by 12.9% to 13.7% when using a thickness of 0.5–2.0 cm PCM layer, which decreased HVAC energy consumption by 37% to 39%, respectively. The study also assessed the cost-effectiveness of PCM by determining a price range per square foot that aligns with the energy savings required for practical use in the KSA. Additionally, the maximum production cost of PCM was identified to ensure it is a worthwhile investment in the country's construction industry.

Dedication

I dedicate this work to my family, whose unwavering support has been a constant source of strength. My deepest gratitude goes to my father, Abdullah, and my mother, Faten, whose continuous prayers and encouragement have guided me throughout this journey. Their understanding and patience, particularly when I had to be away from home to pursue my educational and career goals, have been invaluable. I am equally grateful to my brothers and sisters, whose emotional support has been a cornerstone of my success.

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Chapter 1: Introduction

1.1 Energy Consumption & Climate Change History

In the mid-19th century, the Industrial Revolution represented a significant turning point in human history. The invention of the steam-powered engine and the machine utilization brought prosperity and improvement to industrial sectors worldwide. Heat energy produced from coal combustion was the core driver of the Industrial Revolution; it allowed factories to power machinery and replace muscle and hand tool usage. The demand for coal escalated during the revolution and beyond, as it became the primary energy source for goods manufacturing, railroads, and steamship operations for transportation purposes (History.com Editors, n.d., 2024).

The invention of the internal combustion engine further catalyzed a major shift toward other petroleum fuels (Evolution of Energy Sources, 2022). By the end of the 19th century, petroleum products such as crude oil and natural gas (fossil fuels), in addition to coal, were the primary energy provider for the world economy. Decades later, the dependence on coal, oil, and gas rose markedly within 60 years between 1950 and 2018 from 20,139 TWh to 136,761 TWh, with an average increase of at least 200% every two decades starting from 1920 to 1980 (Our World in Data, 2022) (Fig. 1). However, although the worldwide demand and use of fossil fuel combustion instigated achievement, development, and prosperity, this came at the cost of driving the leading factors associated with climate change.

Climate change refers to long-term temperature shifts and weather patterns (United Nations, 2022). Climate change influences global temperature and precipitation patterns, resulting in extreme environmental events such as hurricanes, forest fires, heatwaves, floods, droughts, and storms (Climate change, NOAA). Although the shift in temperature could occur naturally due to

the solar cycle, human activity—particularly the production of greenhouse gas (GHG) emissions through fossil fuel combustion—has been identified as the primary contributor to climate change.

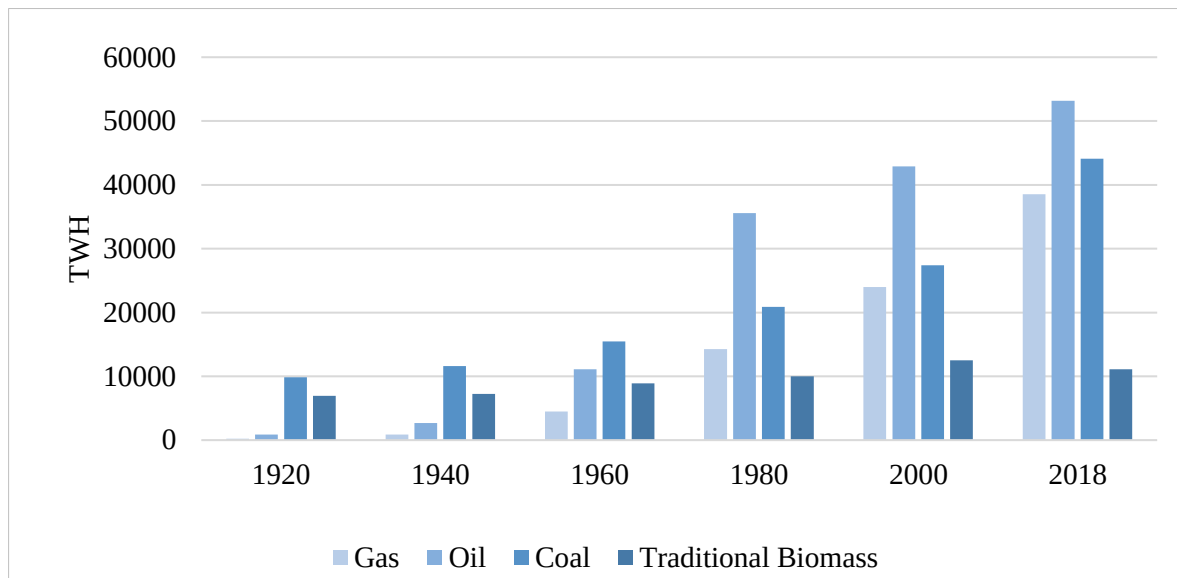


Figure 1. World Energy Consumption by Source (Our World in Data, 2022).

GHG emissions are the direct result of energy production through fossil fuel combustion. GHG is essential in preserving life on Earth by shielding it from the Sun's ultraviolet (UV) radiation which is represented by the Ozone, keeping the planet warm through insulation, and preventing extremes between day and night temperatures (ScienceDaily, 2022). The emission of GHG through human activity increases the atmosphere's GHG concentration, which traps heat by allowing sunlight to pass through the atmosphere but preventing heat reflected by the Earth from escaping back into space. As the concentration of GHG in the atmosphere increases, more heat is trapped, and the Earth's temperature rises (Nikzad & Sedigh, 2017). GHGs include Carbon Dioxide (CO₂), Methane (CH₄), Nitrous Oxide (N₂O), Fluorinated Gases, and Water Vapor. Though each gas plays a role in the formation of climate change CO₂ is the primary factor with 79.7%.

Countries employ various methods for energy production, but at least 29 countries generate 90% of their electrical energy through fossil fuel combustion (Worldatlas, 2017). This heavy

reliance on fossil fuel combustion has led to a substantial increase in CO₂ emissions since the 1800s, from 27 million tons (Mton) to 37 billion tons (Bton) by 2019 (Our World in Data, 2022). The escalation of climate change has become a global concern, prompting countries to take cooperative action to reduce the impact of climate change and control its primary contributing factors.

1.2 The Paris Agreement

Climate change was first observed in the early 19th century, but its causal relationship with CO₂ emissions wasn't discovered until the 1990s (Darkin, 2003). Subsequently, climate change became a concern, but there was no unified global action to limit its effects until the 2016 Paris Agreement. The Paris Agreement was the first legally binding contract between nations to prevent and mitigate climate change, demonstrating a global understanding of the impacts of GHG emissions. The agreement was adopted by 196 countries at the United States Climate Change Conference on December 12, 2015, and became enforceable on November 4, 2016 (UNFCCC, 2022). The agreement has a long-term goal of reducing GHG emissions and achieving net-zero emissions by the mid-21st century, which will mitigate the effects of climate change by lowering global temperatures to below pre-industrial levels (3.6 °F), preferably to 2.7 °F (UNFCCC, 2022).

1.3 The Kingdom of Saudi Arabia (KSA)

KSA, one of the important countries that demonstrated its commitment to the Paris Agreement in 2016, has since taken steps to reduce its carbon emissions and diversify its economy, aligning with the goals of the agreement to combat climate change and transition to a more sustainable future. KSA is a member of the Gulf Cooperation Council (GCC) countries, which are located in the Gulf region known for its hot and arid climate. The temperature usually exceeds 100 degrees Fahrenheit (38 degrees Celsius). The impact of the weather is a significant factor that

affects energy consumption for cooling purposes throughout the year. In addition, electricity in KSA used to be subsidized by the government for its citizens at very low rates, contributing to wasteful energy consumption patterns among the citizens.

In 2019, the Gulf Cooperation Council (GCC) countries were among the top 5 in the world in terms of energy consumption per capita. Meanwhile, the Kingdom of Saudi Arabia (KSA) has consistently maintained its position as the lowest consumer of energy per person among its neighbors with similar climatic conditions, yet it still holds high records of energy consumption throughout the years 2019, 2020, and 2021. According to data from Our World in Data, in 2021, KSA's annual per capita energy consumption was approximately 83,635 kilowatt-hours (kWh) (Fig. 2).

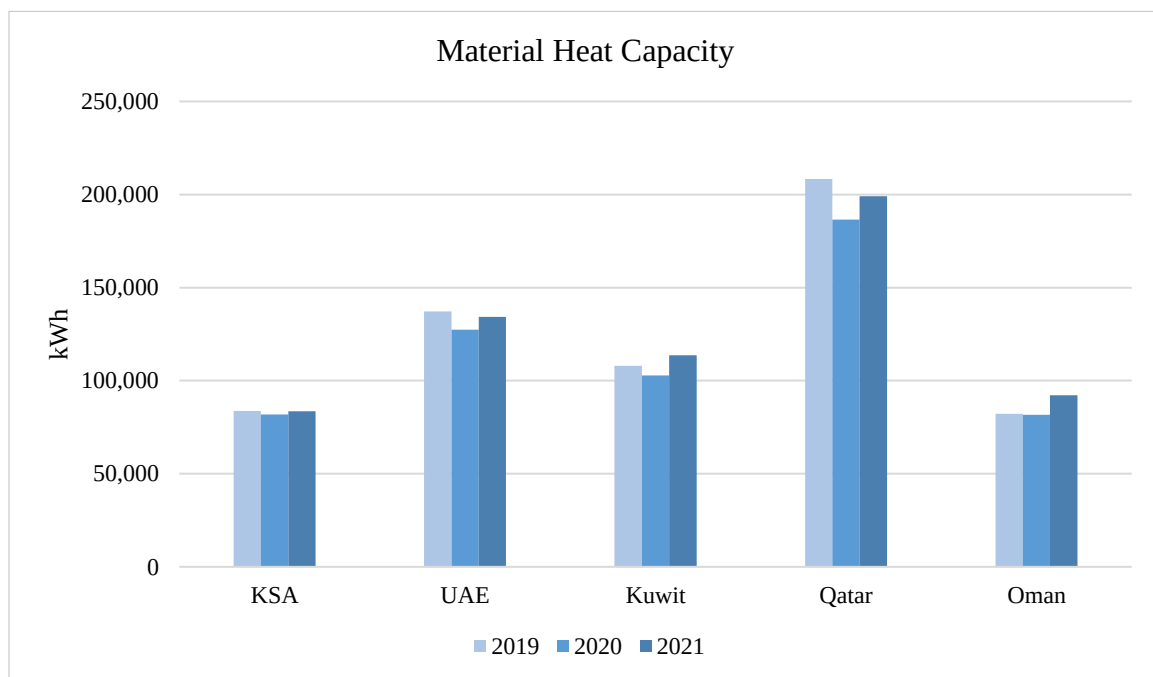


Figure 2. Gulf Countries Energy Consumption Per Capita (Our World in Data).

1.3.1 KSA Energy Consumption

The wealth, self-sufficient energy sources, and government-subsidized low electricity rates, alongside the harsh weather conditions, have encouraged high energy consumption habits in KSA. Subsequently, the country's society has become extremely energy-intensive, with a 99.7% dependency on fossil fuel combustion for energy production in 2020 (Saudi Arabia, 2022). According to the Saudi Energy Efficiency Center (SEEC), there is a high domestic demand for energy in all the country's sectors (2020). In 2020, electricity consumption was led by the residential sector at 48%, followed by the industrial sector at 20%, the commercial sector at 14%, the government sector at 12%, and finally, other sectors at 6% (AlGhamdi, 2022) (Fig. 3). Thus, for KSA to achieve its aim of reducing CO₂ emissions, the residential sector's energy consumption must be reduced.

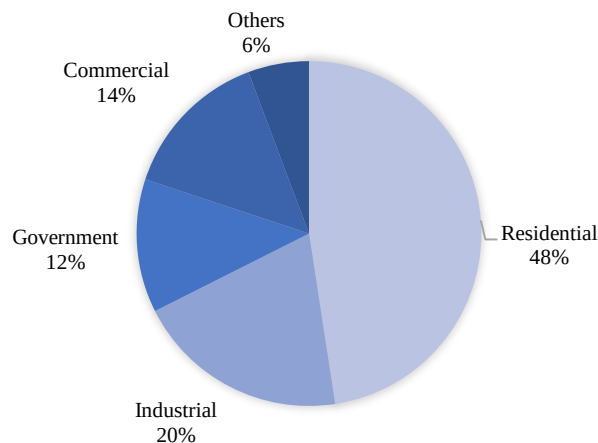


Figure 3. Electrical Energy Consumed by Sector in 2020 (AlGhamdi, 2022).

KSA has an extraordinary economic growth due to the profitability of oil production and exportation, along with the global increase in demand for energy production. The country is one of the leading oil producers and has the second-largest proven crude oil reserves. As a critical provider in the global oil, natural gas, and petroleum products markets, it significantly impacts the

world energy market and economy. Although the country depends significantly on oil and petrochemicals for its revenue and energy, the government still recognizes the importance of diversifying energy sources for a healthy economy, sustainable prosperity, and a sustainable environment. Thus, in 2016, KSA announced its Vision 2030, with one of its primary goals being to embrace sustainability and reduce CO2 emissions by 20% by 2030.

1.3.2 KSA Residential Sector

The residential sector's high consumption statistics and continuous annual increase demonstrate an enduring issue that must be solved. According to the General Authority for Statistics (GASTAT) 2020 report, the residential sector consumed double or triple the electricity of other sectors from 2010 until 2019. This coincided with a slight annual increase (median average of 5.8%) from 2010 to 2016; a slight decrease from 2017 to 2019 (median average of 2.8%); and a rapid increase of 7% in 2020. Moreover, 70% of the electricity is utilized for cooling purposes (Alaboud & Gadi, 2019) (Fig. 4).

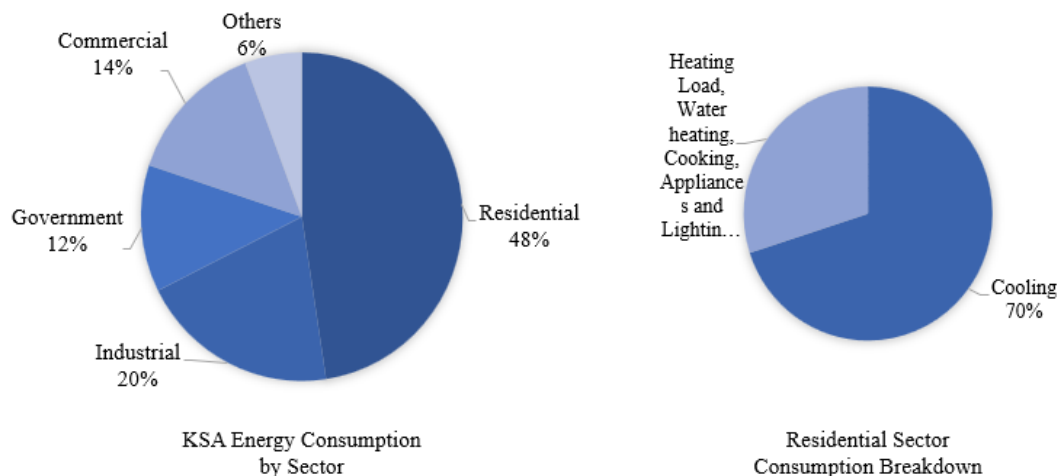


Figure 4. Saudi Residential Sector Energy Consumption Breakdown (Alaboud & Gadi, 2019).

1.4 Global Residential Sector CO2 Emission

The challenge of high energy consumption and CO2 emission in the residential sector isn't limited to KSA; it is a concern on an international scale. According to the UN's global status report for buildings and construction, in 2019, the global building sector's energy consumption remained at 35%, as high as the previous year's record-breaking rate (Global Status Report, 2020). An increase occurred in CO2 emissions from building operations, however, reaching their highest level yet at around 10 gigatons of carbon (GtCO₂), or 38% of total global energy-related CO2 emissions (Fig. 5) (2021). The statistics of residential sector energy consumption and CO2 emissions have shown their impact on the environment through climate change and its related effects. Thus, a solution must be found through architectural design, as the energy performance of buildings is a part of this burden.

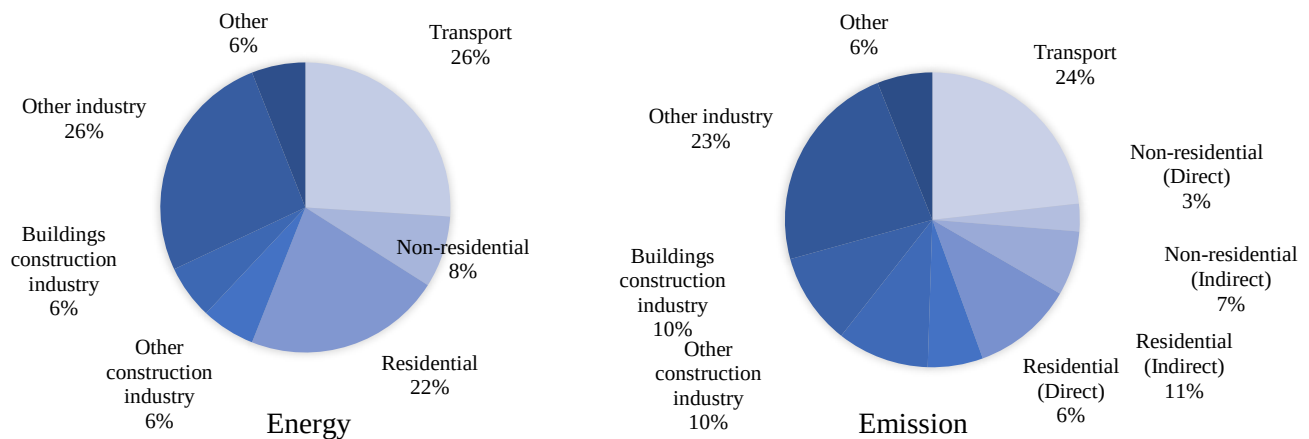


Figure 5. Global Share of Building and Construction Final Energy and Emission (UN Environment Report, 2021).

1.5 Architecture's Role in Building Performance

Throughout history, "architecture" has generally been defined as the construction of buildings based on various objectives and functions that have changed over time and across

cultures. The purpose of architecture has always been not just to build a habitat, but also to represent the culture and power of civilizations across the seven continents (Anas, 2019). Expressive architectural examples worldwide have helped us understand past cultures. Civilizations that have diminished or disappeared over time are embodied in their architecture, which has helped future generations identify, interpret, and understand past cultures, values, and beliefs (Hoskin, 2004). Therefore, architecture is considered an art form of cultural expression and representation throughout history. The question is: what role does architecture serve today?

The objective of architecture has evolved over the centuries as construction goals have changed. In the 1st century AD, the Roman architect Vitruvius stated that a good building must contain durability, utility, and beauty (Westgate, 2018). Two centuries later, Vitruvius's idea was developed by Leon Battista Alberti, who stated that the beauty of a building must be in the quality of its proportions (Vitruvius's theories of beauty, n.d.). Moreover, in the 19th century, architect Louis Sullivan replaced utility with function, which included aesthetic, psychological, and cultural dimensions (Craven, 2022). Although architectural objectives have evolved, the core elements of durability, beauty, and adjusted utility have nonetheless persevered over centuries.

In the late 20th century, the concept of sustainability was added to architectural objectives (López, 2006), asserting that a building should be constructed in an environmentally-conscious way to reduce its negative impacts on the environment. Improving the building's function and performance thus becomes a critical subject of research since these specifications significantly impact the building's occupants and the environment.

Architects, in summary, seek to improve the outcomes of our architecture and enable us to produce a building that meets both aesthetic and functional needs. Each former development in architecture was motivated by contemporary understandings of human needs and was a response

to these needs through architectural design. Architects' knowledge from other fields influences their architectural design and the occupant experience; thus, the architect is burdened to understand and solve any defects in architectural design.

1.6 Impact of Enclosure on Energy in KSA

The harsh weather conditions associated with hot days and cold nights significantly influence energy consumption in KSA's residential sector (Alaboud & Gadi, 2019). The HVAC system provides the indoor occupant with a desired average temperature range. The building enclosures' primary purpose is to maintain the average temperature that the cooling system provides with minimum heat exchange between the indoor and hot outdoor environments. The excessive use of electricity for cooling demonstrates a lack of thermal stability for occupants and low thermal performance of the building envelope.

The enclosure's poor thermal performance in the KSA residential sector is due to the typically-used materials, such as red clay, masonry block, and concrete masonry unit (CMU), which are standard in achieving the traditional thermal mass effect. Thermal mass has been historically beneficial since it is compatible with diurnal temperature swings, but the thermal mass technique should be well calculated and better researched to reach practical results. Some studies suggest adding insulation for optimum thermal performance since the building materials alone are ineffective (Al-Hadhrami and Ahmad, 2009). Unfortunately, homeowners avoid implementing insulation, due in part to the high initial cost and the inexpensive electricity rates; thus, the misuse of thermal mass occurs and produces a high cost, massive wall structures, and a heavy reliance on cooling systems operation for thermal stability. The awareness about the importance of the enclosure thermal performance has become crucial in KSA after the government ceased electricity subsidization, implementing new rates with high prices as represented in (Table 1). According to

Felimban et al. (2019), the new electricity rates resulted in about a 260% increase in electricity bills, leading to a significant rise in energy costs. This situation has caused households to allocate approximately 10-19% of their income to cover their energy bills.

Table 1. KSA Electricity Rate (Saudi Electricity Company).

Previous Rate						
Residential						
(kWh)	1-2000	2001- 4000	4001-6000	6000 +		
(Halalah / kWh)	5	10	20	30		
Commercial						
(kWh)	1-4000	4001-8000	8000+			
(Halalah / kWh)	16	24	30			
Agricultural & Charities						
(kWh)	1-6000	6000+				
(Halalah / kWh)	16	20				
Industrial Sector						
(kWh)	All Consumption					
(Halalah / kWh)	18					
Private educational facilities, private medical facilities						
(kWh)	All Consumption					
(Halalah / kWh)	21					
Government Sector						
(kWh)	All Consumption					
(Halalah / kWh)	32					
New Rate						
Consumption categories	Residential	Commercial	Agricultural & Charities	Governmental	Industrial Private educational facilities, private medical facilities	
1-6000(kWh)	18	20	16	32	18	18
More than 6000 (kWh)	30	30	20			
<i>(Halalah / kWh) = 0.00266 Cents</i>						

If energy consumption is to be reduced in KSA, then implementing a high-performance, cost-effective building enclosure must be the primary strategy. In the global building industry, new building materials and wall systems have been introduced and utilized to build envelopes with high thermal performance and cost-effectiveness. Therefore, KSA must adapt and take advantage of these recently-developed building materials by proposing, implementing, and testing them, rather than continuing to bear the inefficiencies of the current enclosures' low thermal performance.

1.7 Housing in KSA

The Kingdom offers a diverse range of housing types to cover the needs and preferences of its population. Housing preferences vary based on different factors such as income, location, lifestyle, and cultural values. In big cities such as Riyadh, Jeddah, and Dammam, there is a mix of modern apartment complexes and luxurious villas. Citizens living in apartments due to its affordability, which has modern amenities, and proximity to workplaces and commercial centers located around urban centers (Fig. 6). However, Saudi culture places a high value on family and privacy, leading to a preference for single-family villas or spacious homes with a variety of living spaces when it's an affordable choice for extended family members. Due to its high cost and lack of affordability, it's not an option for the majority of families.

The family income average depends on location, occupation, and household variables. The government has developed several economic changes and initiatives to diversify the country's economy and increase its citizens' incomes. However, in major cities like Riyadh, and Jeddah, the average family income tends to be higher due to a greater concentration of employment opportunities and a higher cost of living. For more than 20 years, housing ownership in Saudi Arabia was limited to 40-50%. Houses were primarily offered by private entities and investors at

high-interest rates, with only a limited number of government-backed interest-free loans available. However, following the announcement of Vision 2030 and the housing program in 2016, the Vision has a goal of raising housing ownership with an affordable price range.

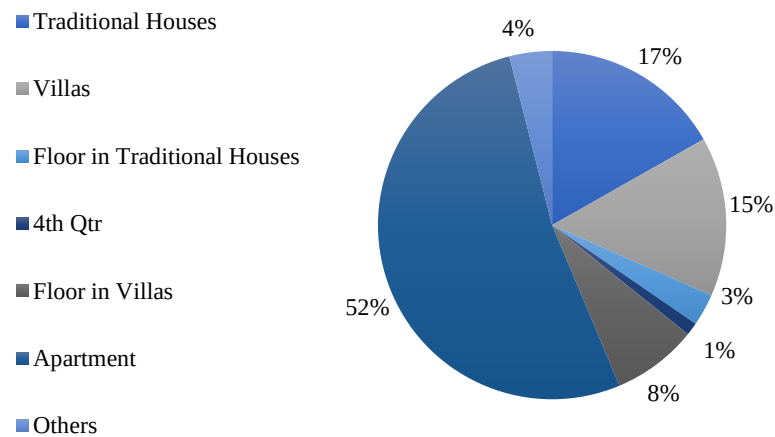


Figure 6. Distribution of Housing Units by Type for KSA Residential Buildings(Krarti, 2020).

1.8 KSA Construction & Housing Demand

Developing the residential sector is critical to achieving KSA's 2030 Vision. The country launched a housing program in 2018 that aims to raise housing ownership in Saudi families. The program's first stage produced a significant achievement by increasing housing ownership from 47% to 60% within three years, far exceeding expectations that had predicted a 15-year requirement for the same results. In the next stage, the program targets the underprivileged portion of their society to increase families' housing ownership to 70% by 2030 (Vision 2030, 2022). Thus, 49 major housing projects were introduced in different areas in KSA to achieve the goal of Vision 2030.

Despite its benefits, the new housing program has also proven problematic due to the high demand for new construction, which exacerbates two major problems in KSA construction: the

labor market shortage and the shortcomings of building envelopes' low thermal performance. Maintaining current standard construction methods for the newly proposed projects has the potential for future disaster in the thermal performance and failure to meet the Vision 2030 housing target. Therefore, an innovative solution must be implemented to address all aspects of the housing challenges in KSA.

1.9 Modular Housing

King Abdulaziz City for Science and Technology (KACST) has adopted the innovative modular housing approach in its construction. It is developing a mega manufacturing facility to produce modular single-family homes with a targeted capacity of producing up to five thousand single-family houses annually, with an area ranging from 500 sq ft to 800 sq ft. KSA construction at large could take the same approach to meet the high demand for construction needed in a short time. Modular housing would be beneficial because the construction occurs off-site under controlled conditions, eliminating undesired site factors such as construction schedules, costs, material waste, safety and security of laborers, and trade workers. Moreover, the modular system produces a model using the same materials and is designed to meet the same codes and standards while taking only half the typical construction time. However, although the modular housing approach presents an intelligent solution to meet KSA construction's high demand, it also must address the thermal mass low performance associated with KSA's standard building materials.

Thermal mass usage produces heavy, thick walls with high thickness for optimal thermal performance. The modular approach's main strategy is to construct off-site and transport the modular unit to the site for installation. A heavyweight unit would cause difficulty in transportation and installation mobility, reducing the modular approach's overall advantages. Historical

dependence on the thermal mass method must be replaced with a compatible alternative to fulfill the modular housing approach's performance and weight factors.

1.10 Phase Change Material

Phase change materials (PCM) can be a perfect alternative to traditional thermal mass construction. Known as latent heat storage material, PCM can change phase when it absorbs and releases heat. It melts and solidifies at specific temperatures, which helps control and stabilize temperatures. In addition, PCM can absorb a significant amount of heat energy with less weight and thinner sections, unlike sensible heat storage materials that shift the temperature of a storage medium without changing its state. Therefore, PCM maybe a suitable alternative for thermal mass in modular housing because it retains the essential properties of thermal mass without its disadvantages.

The KACST project proposes using a high-performance system for light construction incorporated with PCM in modular villas. The light construction is represented by the utilization of structural insulated panels (SIPs). These panels consist of an insulating foam core (XPS) sandwiched between two structural facings, typically oriented strand board (OSB). SIPs are manufactured under factory-controlled conditions and can be fabricated to fit nearly any building design. By using PCM's heat energy absorption and lightweight properties, the approach aims to take advantage of the modular housing method while optimizing the building enclosure's thermal performance and weight.

1.11 Problem Statement

The residential sector in KSA has low building enclosure thermal performance and its related indoor thermal instability, high energy consumption, and excessive CO₂ emission. About 70% of the electricity utilized in the residential sector is used for cooling purposes (Alaboud &

Gadi, 2019) due to the misuse of the thermal mass method, further illustrating a lack of enclosure thermal performance. While the sector addresses enclosure thermal issues, the labor market shortage has drawn additional attention and concern after the Vision 2030's housing project announcement and the resultant increase in demand for new, prompt construction. Maintaining the old construction methodology and application will sustain the enclosure issues and prevent achieving the Vision 2030 housing target. Therefore, KSA is an ideal candidate to adopt the modular housing approach to overcome the construction demand while using PCM incorporated in SIPs to prevent thermal mass drawbacks.

While PCM's high thermal performance and lightweight characteristics represent a significant potential solution for the KSA building sector, the utilization of PCM in modular housing has currently not been explored. This research will examine two essential factors of implementing PCM in modular housing that need more investigation: 1) the assessment of PCM outcomes; and 2) the economic and life-cycle cost analysis (LCCA) consideration in modular housing in KSA.

1.12 Research Goals

1. Investigate the application of PCM in modular housing in KSA.
2. Optimize the enclosure thermal performance to create a stable indoor thermal temperature for the space occupants.
3. Decrease energy consumption in the residential sector and lower its environmental impact.
4. Investigate the LCCA for the application of PCM in modular housing.

1.13 Research Objectives

1. Optimize the placement and thickness of PCM in response to difference climatic conditions and determine the impact on thermal performance.

2. Accurately determine the overall energy savings after optimizing the placement and thickness of the PCM in residential building envelopes in KSA, and identify associated outcomes.
3. Determine the cost-effectiveness of PCM as an investment strategy in the KSA housing construction industry and demonstrate the breakeven price points for PCM manufacturers.

1.14 Research Questions

Main Research Question:

- Is PCM cost-effective for implementation in modular housing in KSA?

Research Sub-Questions:

- What is the ideal placement location and thickness within a wall structure to maximize the PCM thermal performance in KSA?
- What is the overall electricity-saving average of PCM when applied in the building envelope?
- What is the cost of PCM, and at what point does it become cost-effective in terms of electricity rate?
- What is the maximum cost for PCM production to be cost-effective?

1.15 Research Method Overview

This study will utilize a quantitative research design since this approach is suitable for investigating the feasibility of PCM as a cost-effective solution to modular housing construction in KSA. The cost-effectiveness of PCM will depend on the relationships and impacts of a set of independent and dependent variables that are best evaluated quantitatively. The main research tactic is using energy simulation tools to measure the variables' outcomes numerically. The influential variables were identified and data were collected and investigated through a series of

simulations for a specific case study. The data obtained from the simulations was then analyzed and interpreted for use in the LCCA. Chapter 3 will delve further into the research methodology.

1.16 Quantitative Purpose Statement

This study investigated the economic and LCCA considerations for PCM application in modular housing. Therefore, the relevant variables were quantitatively investigated to obtain the necessary results. The accuracy of the LCCA depends on knowing the initial cost of the PCM application, materials and installation, and electrical rates. The study optimizes PCM outcomes first by examining and analyzing the contributing variables through their relationships and impacts upon one another. The antecedent variables were defined as PCM placement location, PCM thickness, and electrical rate. The criteria were identified as the initial cost of PCM application and electrical savings.

1.17 Research Contribution

This research contributes to the body of knowledge in the following ways: 1) it covers the previously unexplored application of PCM in modular housing in KSA; 2) it addresses the need to properly determine the optimum thickness and location of the PCM in the wall assembly, due to their impact on thermal performance, energy-saving, and initial cost; 3) it demonstrates the importance of conducting an LCCA to support decision making; 4) the research suggests the maximum cost to not be exceeded for PCM production to be a cost-effective investment in KSA's construction industry. In addition, the research methodology can be adapted for use in other studies to analyze and optimize construction parameters that contribute to the broader field of sustainable construction and decision-making processes for construction projects on both large and small scales.

Chapter 2: Literature Review

The extant literature illustrates KSA's complex challenges, which compel the research objective to investigate the PCM application's economic and LCCA considerations in modular housing. Accordingly, the literature review will address the following areas: 1) the history of KSA's residential sector's problem of misusing thermal mass with low thermal performance and its associated effects; 2) the problems of the labor market shortage that followed KSA's Vision 2030 announcement, which abruptly brought a high demand for construction and led to a shift in construction methods; 3) the advantages of moving towards modular housing and PCM application in buildings; and 4) the benefits of the LCCA impact in decision making.

2.1 Energy Consumption and Thermal Mass

One of the primary goals of architectural design is to create living spaces that cater to human needs and enhance overall well-being. Achieving thermal stability within these spaces is among these fundamental needs. The building enclosure plays a pivotal role in maintaining a stable interior atmosphere and minimizing heat exchange between the building's interior and exterior. Subpar thermal performance of the enclosure results in increased cooling loads, leading to a lack of thermal stability, which is a challenge evident in the energy consumption patterns in KSA.

Thermal mass has been employed in KSA's building enclosures historically to apply the benefits of the thermal mass. In desert climates, the application of thermal mass effect is suitable. Where diurnal temperature fluctuations allow thermal mass to absorb excess heat during the day and release it as the temperatures drop at night. However, the application of thermal mass must be precise to yield the intended benefits. Unfortunately, KSA's residential sector faces the downsides of misusing thermal mass of high initial costs, bulky wall structures, and challenges related to maintaining indoor thermal comfort. The following three studies will illustrate the historical

reliance on thermal mass, the efforts to improve its function, and the aspects where its application falls short.

The challenge of optimizing energy consumption while ensuring thermal comfort has been a subject of research for over two decades. Ahmad (2002) emphasized that energy conservation should be explored without compromising occupants' thermal comfort, as energy conservation techniques need to be balanced with the occupants' well-being. Incorporating thermal insulation is an essential method for achieving thermal comfort. As Ahmad noted, the drawbacks of avoiding the initial cost of adding insulation are reflected in KSA's high energy consumption. In 1995, the building sector consumed around 73% of electricity, and about 65% of this was attributed to cooling. The excessive electricity consumption for cooling underlines the thermal performance issues within building enclosures.

The study goal is to improve the thermal performance of thermal mass by enhancing the wall structure use. KSA generally has two standard wall structures. The first type consists of an outer layer of plaster, hollow concrete block or brick, plaster), with an R-value of 2.9 ($\text{m}^2 \cdot \text{K}/\text{W}$). The second type involves stone cladding, concrete, an air gap, bricks, and plaster with an R-value of 3.9 ($\text{m}^2 \cdot \text{K}/\text{W}$).

Ahmad conducted these studies in two distinct climate zones in KSA: hot and dry conditions represented by Riyadh City, and hot and humid conditions represented by Dammam City. While there were concerns about the initial cost of adding insulation, not doing so could jeopardize indoor thermal comfort and lead to higher electricity consumption for cooling. The study demonstrated that adding optimal insulation thickness to standard wall structures might increase the initial cost but reduce cooling loads, resulting in lower cooling costs. The study also

found that specific insulation types could yield a return on investment through energy savings within 2.5 years.

A subsequent study revealed that the problem of high energy consumption persisted and extended its impact. The electric industry would not be able to cope with the rapid growth in electrical demand driven by population increase and urbanization (Al-Hadhrami & Ahmad, 2009). The building sector accounted for about three-quarters of total electrical consumption, with air conditioning (AC) in residential buildings contributing 73% to the overall energy consumption due to the low thermal performance of building enclosures, especially in the face of KSA's harsh climate.

Al-Hadhrami & Ahmad tested various masonry block and concrete masonry unit (CMU) samples to investigate how improving thermal performance could reduce energy consumption (2009). Within each group, different insulation methods were applied and assessed. They evaluated the thermal performance of these masonry blocks, taking into account factors such as thermal insulation, insulation techniques, mortar types, size, and general observations. The study measured the thermal resistance of each masonry type by comparing the resistance increase between standard and insulated red clay blocks.

The use of insulation using different methods increased the thermal resistance of normal, lightweight, and insulated red clay blocks by 155%, 188%, and 171%, respectively. Two primary industry methods were employed to enhance the thermal resistance of masonry blocks. The first method involved the direct addition of insulation into the block mixture by creating a lightweight unit with increased thermal resistance. This approach increased the thermal resistance for red clay samples by 9.7% to 15.6% and for CMU samples by 99.5%. The addition of polystyrene insulation into the CMU mix and the use of perlite in lightweight CMU raised the thermal resistance by

100%. The second is to keep the insulation materials separate from the mixture and use them to fill the CMU's cavities. This method increased the thermal resistance by 10% to 32%, which depends on the type of insulation used for filling. Overall, the study underscored the pivotal role and impact of various insulation applications on thermal performance.

Al-Hadhrami and Ahmad also conducted a cost analysis to determine the payback period. Taking into account the block's life cycle, the time value of money, the rising energy costs, and net present worth (NPV) factors. Their calculations showed that the payback period could range from 0.5 to 1.8 years, depending on the type of insulation used and the application method.

In the ten years following Ahmad's study, the issue of high energy consumption in the building sector was not alleviated but became increasingly worse. Felimban et al.'s 2019 study found that KSA's residential sector still comprises 50% of the total energy consumed; the electricity utilized represents about one-third of the country's oil production. In addition to an annual rise in electricity utilization of 5-8%, it is probable that by 2035, oil production and consumption could be equal. To limit energy consumption in 2018, the government announced that the subsidizing of energy bills would cease, leading to a 260% rise in the kilowatt-hour (KWh) price to raise consumers' awareness of their energy usage (Felimban et al., 2019).

Felimban et al. used a survey to measure occupants' behavior roles (2019); 369 surveys were completed in December 2018, with 333 participants living in Jeddah where the study took place. The survey revealed that approximately 70% of participants lack insulation in their buildings; therefore, adding proper insulation is a logical first step towards energy reduction and efficiency. In addition, the survey also collected specific details about thermal comfort. 45.1% of participants preferred indoor temperatures of 22 °C (72 °F) to 24 °C (75 °F), and 34.4% desired to maintain their room temperature at 19 °C (66 °F) to 21 °C (70 °F). The other 8.1% preferred their

room temperature at 19 °C (66 °F). Correspondingly, the majority preferred to keep the room temperature around 19 °C (66 °F) to 24 °C (75 °F) due to affordable electrical rates. In fact, 76% of participants use their AC from 18 to 21 hours per day, while only 9% use it for less than 10 hours per day.

These first two studies shared concerns related to high energy consumption drawbacks in KSA, noting how the buildings' thermal enclosure performance impacts indoor thermal stability and cooling loads. Ahmad's study (2002) stated that the building sector consumed about 73% of energy in 1995, and about 65% of that load was through cooling load consumption. After analyzing this data, Al-Hadhrami and Ahmad had similar concerns about the impact of high energy consumption on the environment (2009). They found an increase of 6.2% in energy consumption, 73% of which was exhausted on cooling loads due to KSA's hot and humid climate regions. The two studies asserted the necessity of enhancing buildings' enclosure performance by adding insulation and showing its benefits on cooling load reduction.

Felimban et al.'s study a decade later (2019) demonstrates the same concern about the challenge of high energy consumption in KSA, noting that residential buildings consume 50% of all energy consumed by buildings. This observation highlights the importance of the building envelope as a thermal protector from outside natural forces, and the need to reduce this impact by optimizing buildings' thermal performance. The initial research has centered on developing and effectively enhancing thermal mass material for two decades. However, the proposed solution of adding insulation to the building enclosure has not been largely applied. When electricity rates are so low, the industry is reluctant to move toward a solution with high initial costs and a labor shortage, despite its overall long-term benefits.

The initial cost is one of the main factors that compels owners to avoid insulation applications or any other approach to maximize building envelopes' thermal performance. With the previous subsidized electricity rates, the initial cost was not cost-effective. However, according to Felimban et al. (2019), the 260% increase in electricity bills significantly impacted people's finances, with 62.6% of households now using about 10-19% of their income for electricity bills. The electricity rate increase has heightened awareness of electricity usage and encouraged solutions, rendering the initial cost of adding insulation to thermal mass cost-effective. However, the labor shortage still requires a solution to support the Vision 2030 housing goal.

2.2 Labor Shortage

The construction sector lacks skilled local labor and relies on laborers from outside the country which makes the labor shortage a persistent issue for KSA's construction industry. Unfortunately, due to the high demand in the construction industry; skilled laborers are often recruited by high-quality companies for large projects financed by the government. Consequently, unskilled laborers are left with opportunities to gain experience until they become qualified for higher-paying jobs. This practice is typically implemented on small projects such as villas and residential buildings, which are the most common building types in KSA. According to Al-Emad and Rahman (2018), eight construction managers identified a shortage of qualified workers as one of the main challenges for their projects in Makkah, KSA. However, in previous years, the labor shortage was not a critical concern for the residential industry because it was progressing at a slower pace, and the demand was in line with the available workforce. When the Vision 2030 housing program was announced in 2018, new housing projects were initiated in various locations within KSA (Vision 2030, 2022). The program aimed to increase housing ownership for KSA families within a short timeframe, which created a genuine concern about the labor shortage to

meet the significant increase in construction demand. The sudden surge in construction demand, coupled with the existing labor market issue, provides a strong incentive for the KSA construction industry to consider meeting its goals through modular construction.

2.3 Modular Housing Approach

Modular housing is a construction approach that has gained widespread attention and popularity in the last five decades due to its innovative and efficient methods for building residential structures. It stands in contrast to traditional construction methods. In this approach, identical models with consistent design intent and specifications are constructed off-site under controlled plant conditions, then delivered and installed on-site using the same materials (Bertram et al., 2019; Ogden et al., 2014) (Fig. 7). According to Ogden et al., the key advantages of modular construction include: 1) a faster return on investment due to shorter construction times and reduced on-site management costs; 2) superior quality ensured by the factory-based construction process; 3) economies of scale in production, particularly in large-scale repetitive projects with exact specifications; 4) reduced design costs; and 5) a decrease in worksite accidents (2014).



Figure 7. Modular Housing Application (D/O Architecture, 2023).

In Agha et al.'s research, they illustrated the importance of the modular construction approach in the field of construction across various sectors (2021). The investigation focuses on applications of modular housing in the UK housing market. Several construction-related issues have been taken into account in the study, such as availability and cost. Examining the difficulties and effects associated with modular construction in the UK housing market is the main goal of the study. In addition, evaluate current industry practices for possible application in the UK housing sector and obtain a comprehensive understanding of the fundamentals of modular construction.

According to the research, modular construction has a lot of potential to establish itself in the market because of its advantages over other building methods in terms of sustainability and carbon emissions reduction. By eliminating the need for transportation to the site, this method lowers CO2 emissions and reduces material waste through reuse and recycling in factories. Because modular housing is high-quality, time- and money-efficient, and meets growing housing needs, it has the potential to gain widespread acceptance.

In another study by Musa et al., they aimed to investigate the benefits of applying and adopting modular construction in the Malaysian construction industry through a case study. In their research, they explored the definition, history, benefits, applications, and characteristics of modular construction. The research highlighted the following advantages of using modular housing:

1. **Faster Project Delivery:** Modular buildings can be built concurrently with site preparation and foundation work while the modular units are produced off-site, saving time compared to the traditional on-site construction process. Due to significant time savings, projects are finished 30% to 50% quicker than with traditional construction.

2. **High-Quality Materials:** Modular units are manufactured in a factory using high-quality materials and strict quality control. Modular buildings are similar to conventionally constructed structures on a construction site when it comes to building standards and the materials used. They use typical construction materials, such as wood, concrete, and steel, as specified by the design, which are commonly used in the construction industry for building materials.
3. In remote locations such as the hills, where it is difficult and expensive to employ conventional techniques, modular construction is a great option for projects. When a house is built modularly, every component—including the finishing touches—is manufactured off-site. Thus, in remote construction, the main activities are to assemble the modular components and work on the foundation, while the large-scale construction is finished at the off-site factory.

Modular housing is a promising solution to the challenges facing KSA starting from the labor shortages and high demand in the housing sector, to the added benefits of affordability, sustainability, and construction speed. It represents an innovative approach and design flexibility which make it an attractive option for homeowners, builders, and communities seeking modern, efficient, and environmentally conscious housing solutions.

Despite the advantages of the modular approach, still the thermal mass method cannot feasibly be applied. The modular approach depends on producing units off-site and transporting them to be erected on-site for lightweight units with smooth transportation and mobility. In contrast, thermal mass typically requires high-weight units of excessive thickness, which negates the benefits of the modular approach. Thermal mass must be substituted with a suitable alternative that can perform similarly to thermal mass but with a manageable weight.

2.4 Thermal Mass vs. Phase Change Material

Phase change material (PCM) is a material that possesses thermal mass characteristics but is lightweight and offers numerous advantages. Using PCM in modular housing significantly improves the enclosure's thermal performance and reduces the typical wall thickness of buildings in KSA. The minimum wall thickness found in KSA buildings is 25 cm (10 inches) with an R-Value of 2.9 ($\text{m}^2\cdot\text{K}/\text{W}$) (Ahmad, 2002), as thermal mass materials require greater thickness than PCM to store the same amount of heat (Cabeza et al., 2015).

Thermal mass concept is utilized to manage the heat transfer from the external environment to the interior spaces. It is a conventional method that uses structural materials to provide inertia to temperature variations. The material structure acts as a thermal battery, buffering heat transfer into interior spaces by storing heat during warm periods. Incorporating PCM into the building structure increases its heat capacity to act as thermal mass by increasing the material heat capacity.

2.4.1 Thermal Heat Storage

Thermal energy storage (TES) systems preserve energy in thermal form for later use. TES systems involve three primary phases: thermal charging, thermal storage, and thermal discharging, as shown in Figure 8 (Cabeza et al., 2015). These materials can store heat through three main mechanisms: sensible heat (SH), latent heat (LH), and chemical reactions (CH). Starting with Sensible heat (SH) storage which involves an increase in a material's temperature due to heat retention as occurs in thermal mass materials. The material's heat storage capacity is primarily determined by three principles: the specific heat of the medium, the quantity of material, and temperature differences. In latent heat (LH) storage as noted by Mahlia et al. (2014), in contrast to (SH) thermal energy is saved or released when a material undergoes a change in state, such as transitioning from solid to liquid, as observed in PCM materials (Fig. 8). PCM serves as a latent

heat (LH) storage system by absorbing or releasing thermal energy at various controlled temperatures. Additionally, PCM undergoes a phase change by storing and releasing substantial amounts of energy around a specific temperature corresponding to the material's phase transition temperature (Fig. 9).

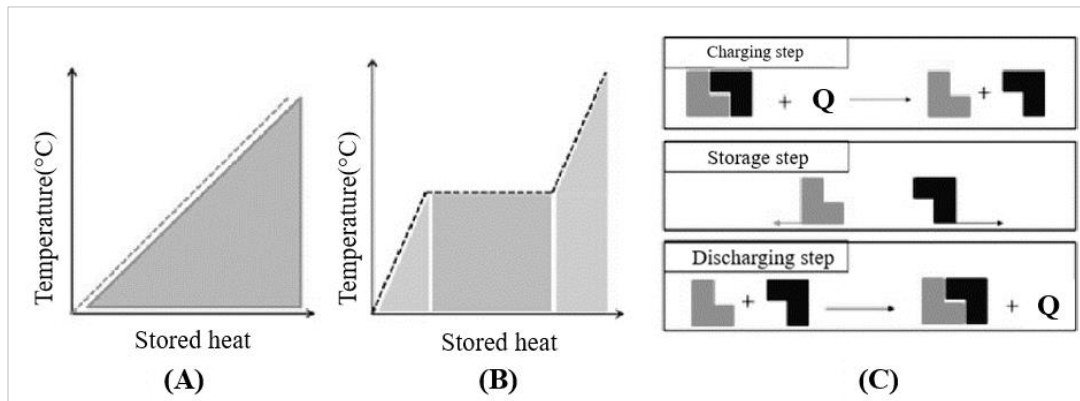


Figure 8. A comparison between (A) sensible heat and (B) latent heat storage and (C) chemical storage (Moral et al., 2017).

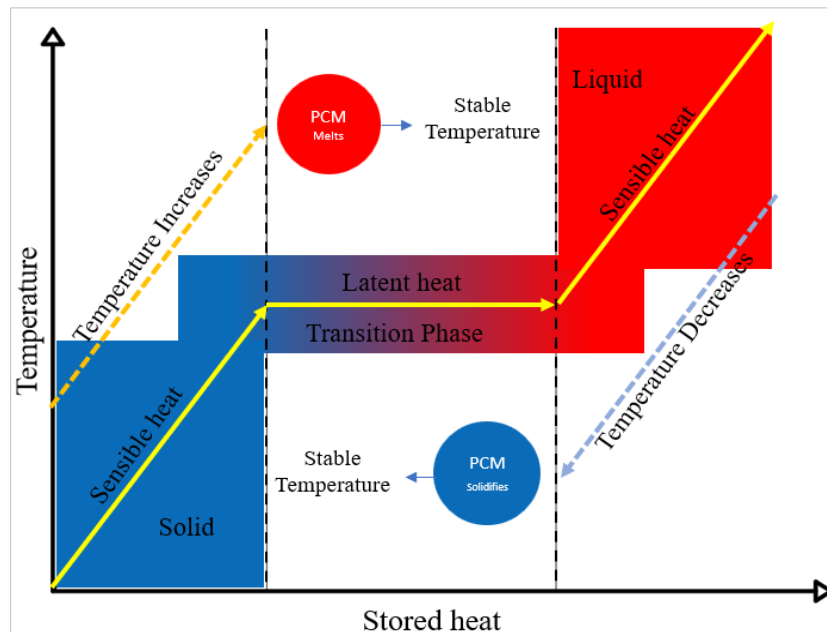


Figure 9. PCM Concept (Phase Change Material, 2022).

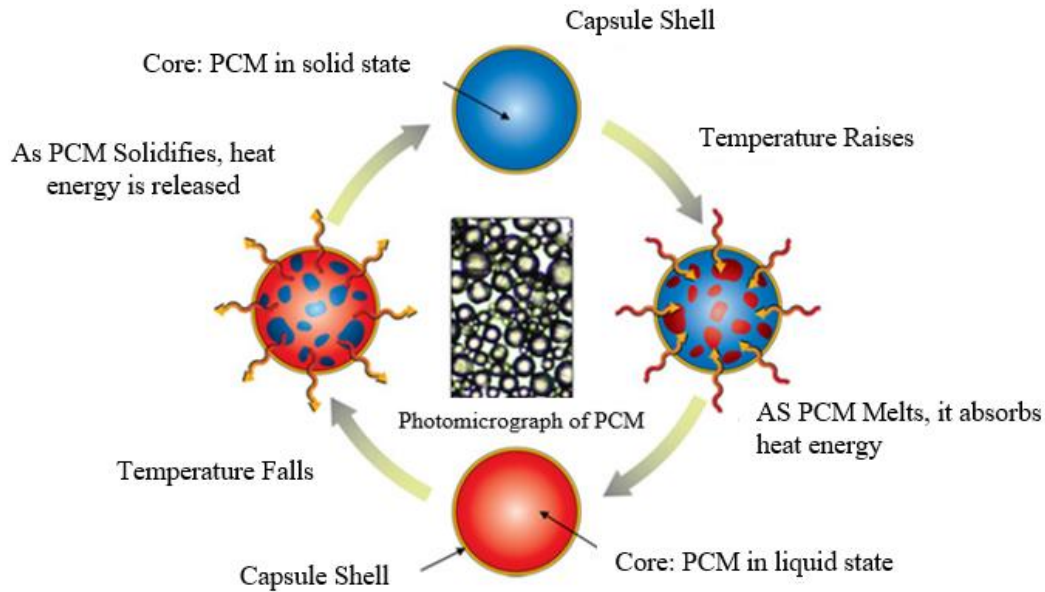


Figure 10. Phase Change Material (microtech).

Akeiberto et al.'s (2016) research identified three classifications of PCMs: organic, inorganic, and eutectic (Fig. 11). Organic PCMs have a wide range of options which make them attractive for research due to their additional latent heat capacity and suitable transition phases with consistent physical and chemical properties. Paraffin and non-paraffin organic PCMs are the most widely utilized varieties because of their advantageous characteristics. However, organic PCMs can be tricky because they are flammable and have low thermal conductivity. Comparatively speaking, inorganic PCMs have a higher heat of fusion per unit mass, are typically less flammable, and are more affordable. Still, they lack thermal stability and are susceptible to corrosion and decomposition, which counterbalances their other advantages. Among inorganic PCMs, salt hydrates are the most commonly used type, offering variety and being widely studied for thermal storage applications. Eutectic PCMs combine at least two classes of PCMs, enabling

mixtures of inorganic and organic, inorganic and inorganic, or organic with organic. This allows them to maintain the benefits of both classes and enhance application functionality.

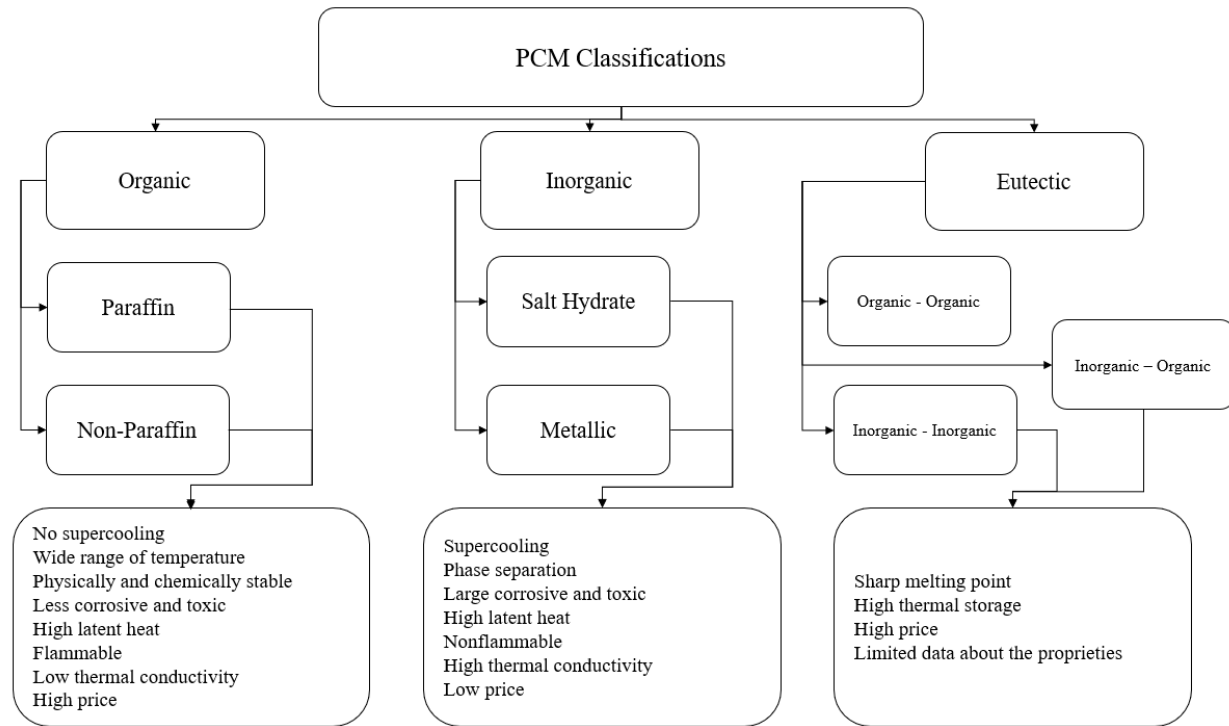


Figure 11. PCM Classifications (Akeiberto et al.'s, 2016).

2.4.2 PCM Application in Building

In recent years, PCM applications have become common in various industries, including the space industry, and for diverse purposes such as solar cooling, solar power plants, solar dryers in the agricultural sector, photovoltaic electricity systems, food, and pharmaceutical product preservation, waste heat recovery systems, and domestic hot water (Zhou et al., 2015). The use of PCM in the building industry has also driven PCM development. PCM manufacturers have created different types and forms of PCM to cater to specific applications and requirements, meeting the performance and industry standards (Fig. 12).

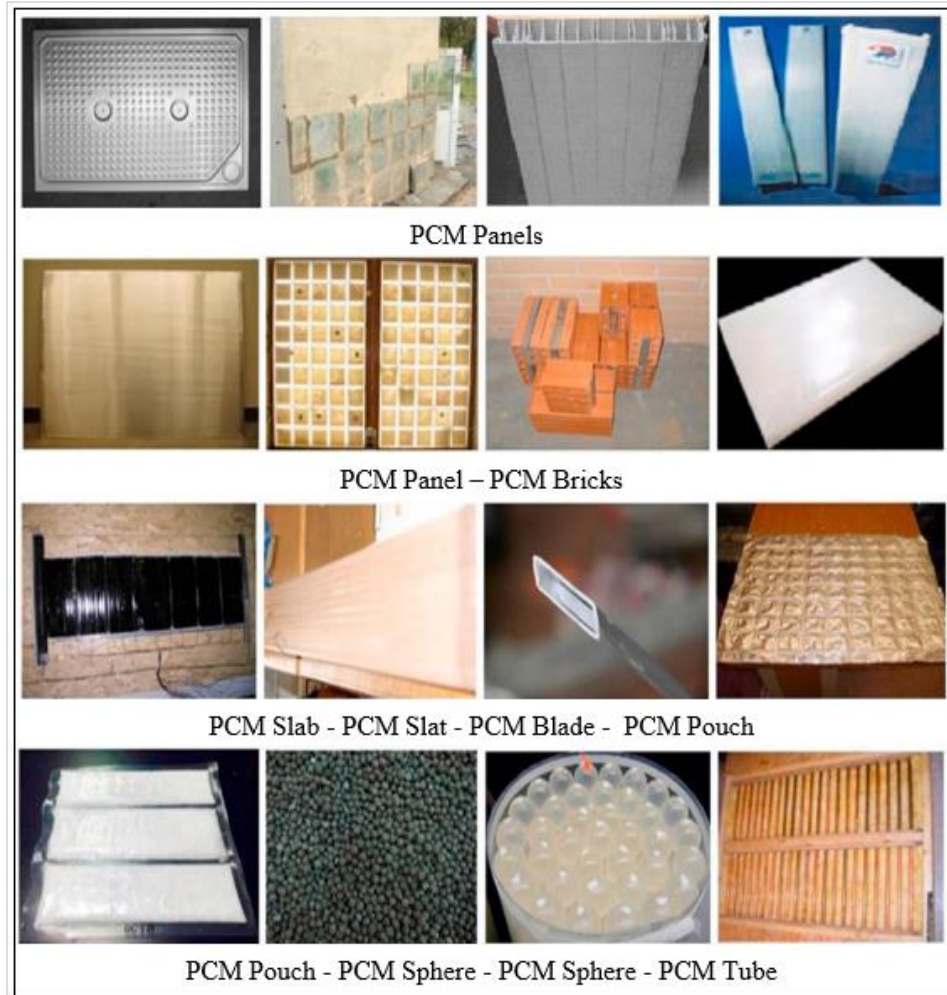


Figure 12. Types and Forms of PCM Developed by the Industry (Al-Yasiri & Szabó, 2021).

The advantages of using PCM have been demonstrated through research. In their study, Shilei et al. (2006) investigated the average heat transfer in a designed room with the application of PCM wallboards. The experiment took place in the northeast of China during the winter season. The study used two models to monitor heat transfer from inside to outside in cold weather: 1) an ordinary room with regular walls and 2) a room with PCM walls. In the PCM wall room, PCM wallboards made of PCM and gypsum boards were used, and these wallboards were attached to the surface of an ordinary room wall to create the PCM wall room. The study monitored both models under similar ambient environmental conditions. The thermal performance of the two

models was compared and analyzed. The impact of applying PCM wallboards showed the capability to reduce temperature fluctuations inside a room and lower electricity costs. Additionally, the use of PCM was found to be cost-effective for heating equipment sizing and investment.

In another experimental study conducted by Muruganantham et al. in 2010 on BioPCM, the research was carried out in Tempe, Arizona, within the Phoenix metropolitan area, at the Arizona Public Service (APS) Solar Testing and Research (STAR) facility. The experimental setup utilized two identical sheds, denoted as 'north' and 'south,' with dimensions of 4.8m x 3.6m x 2.4m (16'x 12'x 8') and featuring a 4/12 pitch roof. Both sheds were oriented to the east, situated in an unshaded location, and allowed unobstructed wind flows.

The North shed had BioPCM installed, but the South shed was built traditionally with no BioPCM installed. The purpose of the study was to look into how the PCM application affected the sheds' thermal performance. Accurate results were measured by using two Honeywell 7500 series 7-day programmable thermostats and identical Amana AH093 window-mounted heat pumps in both sheds.

The study showed significant cost and energy savings, a shift in the peak load time, and a decrease in energy consumption. The highest energy savings were recorded in November, at nearly 30%, and the lowest, at roughly 9%, in March. Solar radiation was the main cause of these notable phase shifts that occurred during the winter. Based on an analysis of NREL weather data for Phoenix, there were no days with temperatures above the PCM transition point (from solid to liquid or vice versa) during the winter months of January, February, and December. BioPCM, characteristics prove to be a promising technology for energy conservation in buildings.

Karaman et al. (2011) reported that infusing building materials with PCMs offers a promising opportunity to provide the building industry with efficient energy storage solutions. The application of PCMs in recent years, including both inorganic and organic PCMs, as well as their combinations, has become a hot topic for researchers investigating the integration of PCMs into common building materials. In particular, Polyethylene glycol (PEG) PCM has garnered significant interest due to its characteristics, which include an appropriate phase change temperature, high latent heat capacity, the absence of supercooling, minimal volume change during phase transition, and long-term thermal and chemical stability.

The study tested the thermal performance of the prepared composite PCM wallboard. Six identical composite wallboards were fabricated by pouring the prepared slurry (PEG/diatomite composite and adhesive) into a stainless steel mold. Two samples were tested using halogen tungsten lamps (250 W) as the heat source for each cell. The variation in temperature on the inner and outer surfaces was monitored using a data logger and recorded using thermocouples (Pt–RhPt) with an accuracy of ± 0.18 °C. The research revealed that PEG/diatomite wallboard has the potential to reduce the peak cooling load and increase building energy efficiency. Furthermore, the PEG/diatomite wallboard performs better than several other composite PCMs that were discovered in the research literature review.

In Mehling and Cabeza's book (2008), they present a comprehensive exploration of the utilization of Phase Change Materials (PCMs) in various applications, including both heating and cooling. The book introduces the concept of PCMs and their significance in thermal energy storage. It explains the fundamental principles of PCMs. In the section on PCM potential and temperature control applications, the study compares common construction materials in terms of their heat storage capacity. The study reports that a 1 cm (0.4 in) layer of PCM can retain as much

heat as an 18 cm (7 in) layer of brick and a 24 cm (9 in) layer of concrete (Fig. 13). Therefore, the incorporation of PCM, even in small amounts within the building structure, can significantly enhance the wall's thermal performance. The addition of PCM can transform a lightweight building into one that performs like a massive structure in terms of thermal comfort.

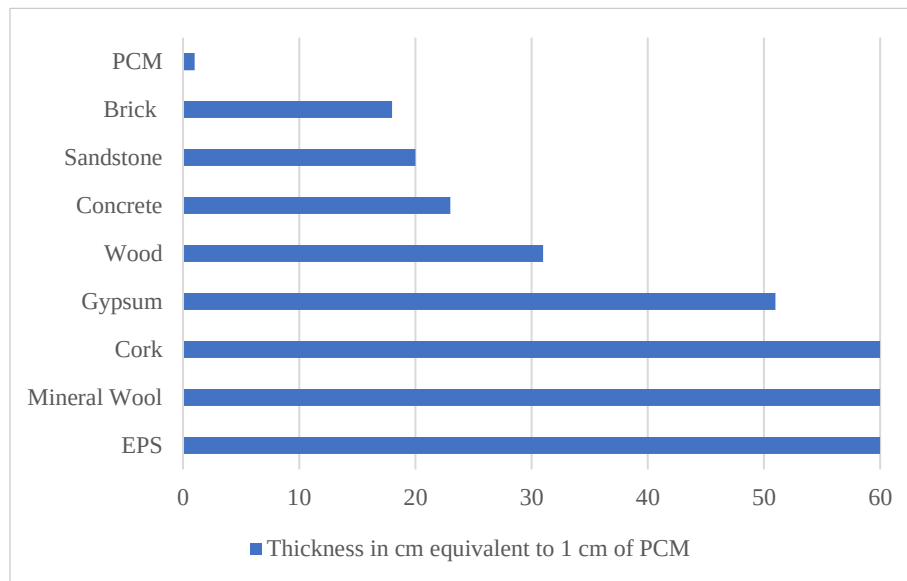


Figure 13. The Minimum Thickness of Diverse Building Materials Needed to Match the Heat Retention of a 1cm Layer of PCM (Mehling and Cabeza, 2008).

To support the findings of the previous study regarding the high heat capacity of PCMs, we examined Akeiberto et al.'s 2016 study, which reviews recent research on the utilization of PCMs in buildings for passive cooling. The study compared the thermo-physical properties of common materials used in building envelopes with a selected set of PCMs (Fig. 14). It is readily noticeable that typical building materials generally have much lower heat capacity than PCMs, making them unreliable for thermal storage due to their low heat conductivity.

The benefits of increasing thermal mass in lightweight structures are evident, as it helps mitigate temperature fluctuations during hot seasons, especially when exposed to high solar radiation. These benefits extend to the winter season, as PCMs can serve as insulators, reducing

heating loads. PCMs can also mitigate overheating during hot daytime hours and reduce heating needs during the cold nighttime hours in the winter.

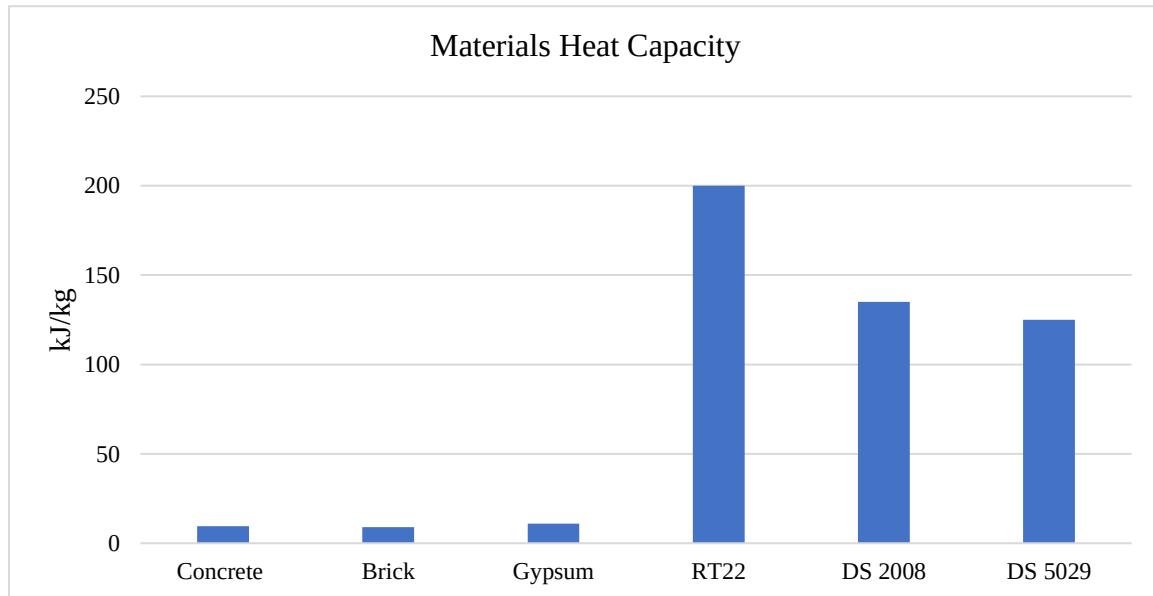


Figure 14. Comparing the Heat Storage Capacity of a Selection of Commercial PCMs with Typical Construction Materials (Akeiberto et al.'s, 2016).

The performance of PCM in building construction has shown promising results. Still, crucial factors need to be considered when using PCM in the building envelope to maximize the function of PCM and increase its energy-saving benefits. The melting point of PCM should be selected according to the building location's specific site, with attention given to the climatic conditions and its day and night temperatures (Sarı, 2014). Furthermore, the chosen PCM should have high latent heat per volume unit, heat capacity, and high conductivity for faster response (Barreneche et al., 2014).

2.5 Life Cycle Cost Analysis (LCCA)

The overall cost of a facility can be calculated using an LCCA. This accounts for the expenses related to purchasing, maintaining, and disposing of a building or building system. LCCA is particularly useful for project options that satisfy the same performance requirements but vary

in terms of beginning costs and running costs, which must be compared to choose the one that optimizes net savings. LCCA assesses the benefits of using different alternatives by comparing all the costs associated with their application to their saving, function, or defined variables (Illankoon & Tam, 2020).

The application of LCCA has shown its impact through research on improving construction projects and related areas. Rad et al.'s 2021 study has highlighted the importance of the cost variable in building design and decision-making. In normal situations, choosing the cheapest available options to maximize profit. The designer's solution is using tools to develop cost assessments for the best and most cost-effective options in the early stages. The goal is to design and build buildings that provide high performance and durability for users by taking into consideration extreme weather conditions or environmental issues. These types of buildings are usually more complex and come with higher initial costs. Creating a resilient method for estimating a building's costs in the early stages will enhance its performance in terms of structure, energy efficiency, and cost-effectiveness.

The research method takes into consideration the cost of various building elements that might be affected in the event of an earthquake. The research addresses this by employing building information modeling (BIM) coupled with cost analysis BIM-LCCA. In addition to the structural performance of the building, the study also considers the performance of the mechanical systems for cooling and heating and their costs throughout the building's life. The study has taken into account all costs, including operation and maintenance, during the early design phase.

The study's results show that the proposed framework is validated through the development of two residential building design options. The study demonstrates that by increasing the initial cost by 4.6%, the annual expected failure cost decreases by 35.4%, and the total life-cycle cost is

reduced by almost 10.4% within the first 45 years of operation. The application of the study's developed method, BIM-LCCA, has reduced the potential for human fatalities, improved building performance, and provided designers with better cost-effectiveness through LCCA estimation.

In another study, Abou Hamad & Abu-Hamd stated that investigating the economic aspect of building alternatives in construction systems has the potential to reduce the costs of the building construction industry. This industry typically accounts for 5% to 10% of the total Gross Domestic Product (GDP). To achieve optimal economic performance and meet sustainability requirements in a construction project, the best approach is to use Life Cycle Cost Analysis (LCCA) to explore effective building design options. LCCA is employed to examine the economic aspect by assessing the cost-effectiveness of different building designs and selecting the option with the lowest life cycle cost (LCC).

The study's methodology is to create a framework that facilitates decision-making by calculating the life cycle costs of various building systems. This framework is developed to be used in the early stages of design to help with critical decisions about building systems selection. It consists of four key elements: defining design alternatives for evaluation, introducing essential parameters for life cycle cost calculations, applying life cycle cost analysis to assess alternatives from an economic perspective, and conducting an analysis to select the most optimal alternative. The study aims to enhance decision-making processes in the selection of cost-effective and sustainable building systems. Additionally, the methodology integrates BIM, energy modeling, and end-of-life scenarios.

In the framing part of the study, the method was used to compare the cost-effectiveness of three different framing systems: the reinforced concrete (RC) framing system and the cold formed steel (CFS) framing system to assess the life cycle cost of the stainless steel (SS) framing system.

The life cycle cost of the SS framing system was found to be 13.4% higher. The application of LCCA has demonstrated the benefits of exploring different building system options by showing the advantages and disadvantages of each option and providing users with a clear vision for selecting the best system to be utilized.

In conclusion, the utilization of LCCA has shown its benefits in exploring different options and aiding decision-making. In our case, the utilization of PCM has shown remarkable results in altering thermal mass utilization, but the cost-effectiveness of using PCM in modular housing has not been thoroughly researched. Therefore, this study will perform an LCCA to determine if PCM is economically feasible for utilization and, if not, what options would make its utilization possible. Moreover, LCCA will be used to determine the feasibility of using PCM in modular housing as an investment by comparing its overall energy-saving potential to the initial and associated costs of the application.

2.6 Research Contribution

The literature has demonstrated the issues facing KSA's building sector. First, misusing thermal mass leads to low thermal performance, resulting in poor indoor thermal stability, high energy demand for cooling, and excessive CO₂ emissions. Second, the increased housing demand cannot be met with KSA's current labor market shortage. These two issues require KSA to move toward modular housing and use alternative thermal mass applications like PCM. Therefore, this study aims to investigate the application of PCM in modular housing, pairing the benefits of PCM's thermal performance and modular housing's advantages in construction demand.

This study aims to enhance existing knowledge by: 1) Examining the use of Phase Change Materials (PCMs) in modular housing in Saudi Arabia (KSA); 2) Investigating the optimal thickness and placement of PCMs and their significant impact on thermal performance, energy

efficiency, and initial construction costs; 3) Highlighting the relevance of Life Cycle Cost Analysis (LCCA) in measuring the impact of initial costs and PCM energy-saving attributes, aiding informed decision-making; and 4) Determining the maximum production cost of PCMs required for them to be cost-effective and competitive within KSA's construction industry. Additionally, the research methodology is adaptable for use in other studies to evaluate and refine construction parameters, advance the field of sustainable construction, and improve decision-making for construction projects.

Chapter 3: General Overview of Proposed Methodology

Chapter 3 provides an overview of the proposed research methodology and explains why the researcher chose a quantitative approach. Additionally, this chapter demonstrates the logical reasoning and appropriateness of the research design and the quantitative tactics employed to investigate PCM variables and address research questions (Fig. 15).

Chapter 3:

- **Overview of Research Approach**
- **Identifying PCM Variables**
 - *Exogenous variables*
 - *Endogenous variables*
- **Research Scope**
- **Quantitative Tactics**
 - **Energy Simulation Tactic**
 - **Energy Modeling Scope and Boundaries**
 - *Simulation Software Selection*
 - *Case Study Tactic Argument*
 - *Case Study Selection & Specifications*
 - *Base Case Characteristics and Variants*
 - **Phase Change Material Selection**
 - **Simulation Context & PCM Application**
 - **Optimization Criteria and Metrics**
 - **Optimization - Weighting of the Parameters**
 - **Initial Cost**
 - **LCCA Phase**
 - *Cost Modeling Uncertainties Over Time*

Figure 15. The Diagram Illustrates Chapter 3 Stages.

3.1 Overview of Research Approach

The study aligns closely with the positivist paradigm, which emphasizes objective, empirical investigation and the scientific method. The utilization of computer simulations and statistical analysis methods reflects positivism's commitment to understanding cause-and-effect relationships based on observable, measurable data. Positivism is an ideal philosophical foundation for investigating the application of PCM.

Research approaches are defined as “plans and procedures for research that encompass the steps from broad assumptions to detailed methods of data collection, analysis, and interpretation” (Creswell, 2014). The chosen research approach should be initially formulated based on the researcher's philosophical worldview and the beliefs being investigated. Additionally, one must consider the research strategy employed within the approach, the methods of data collection, analysis, and interpretation (Fig. 16), as well as the nature of the problem the research aims to address.

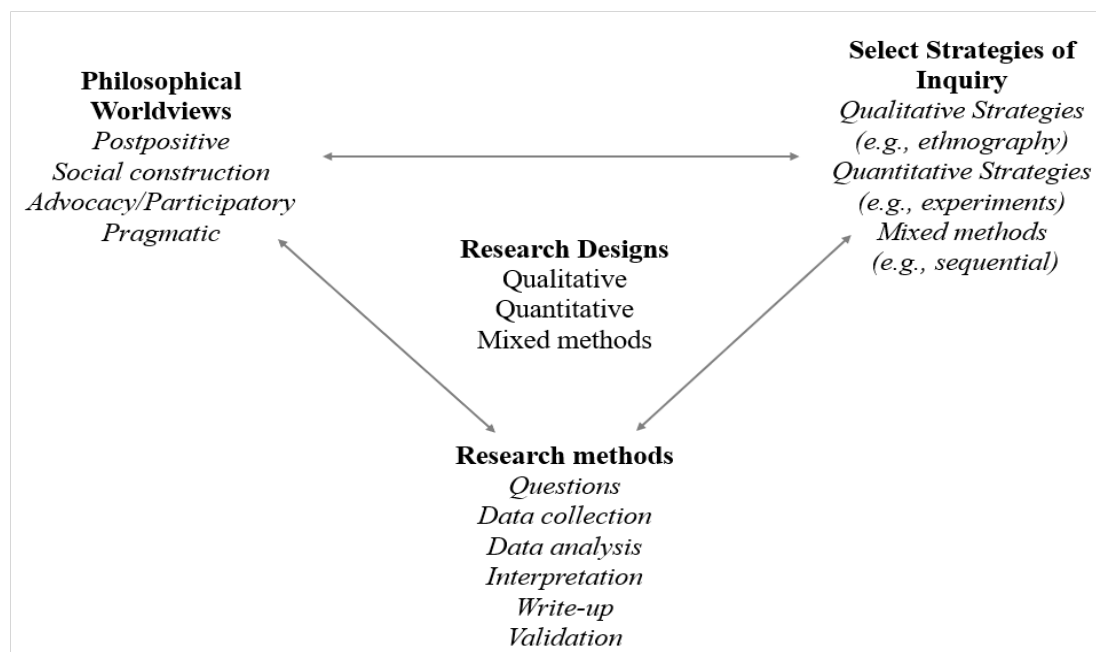


Figure 16. A Framework for Design—The Interconnection of Worldviews, Strategies of Inquiry, and Research Methods (Creswell, 2014).

The proposed study aims to assess the feasibility of implementing PCM as a cost-effective solution for modular housing in KSA by investigating the relationship and impact of independent and dependent variables on one another. The research will quantitatively measure variable outcomes using a computer-simulation tool. Subsequently, the collected data will be analyzed and interpreted through LCCA analyses to evaluate the cost-effectiveness of PCM in KSA's modular housing. While the qualitative approach explores various aspects of human life, such as expression, beliefs, morality, and stress, through research designs like case studies, ethnography, grounded theory, and more (Wertz, 2011), it does not apply to the current study's investigation and data collection method, so it will not be used.

On the other hand, the quantitative approach tests research theories by examining the relationship between variables that can be numerically measured using instruments and then analyzing them through statistical procedures (Creswell, 2014). This approach employs scientific methods to hypothesize and test relationships among variables to explore and develop a study (Creswell, J. W. & Creswell, J. D., 2018). Therefore, the quantitative approach is chosen for this study because its application of the scientific method is well-suited for the research's investigative and inquiry types. Furthermore, the researcher's philosophical worldview plays a role in selecting the research approach. The current study's investigation method and research strategy align with the positivist philosophical worldview, which focuses on identifying and assessing the influence of causes on the outcomes.

3.2 Identifying PCM Variables

The answer to the study's central question depends on the outcomes of the LCCA investigation. The structure and accuracy of the LCCA require the determination of two key variables: 1) the initial cost of PCM application and 2) the optimal electrical savings variables

output. To obtain these two variables, the application of PCM must be optimized by first examining and analyzing the contributing variables, their relationships, and their impact on each other. Therefore, both exogenous and endogenous variables must be identified and quantitatively investigated. Exogenous variables are measures established outside the model and imposed on the model, while endogenous variables have values acquired by the model (Fig. 17).

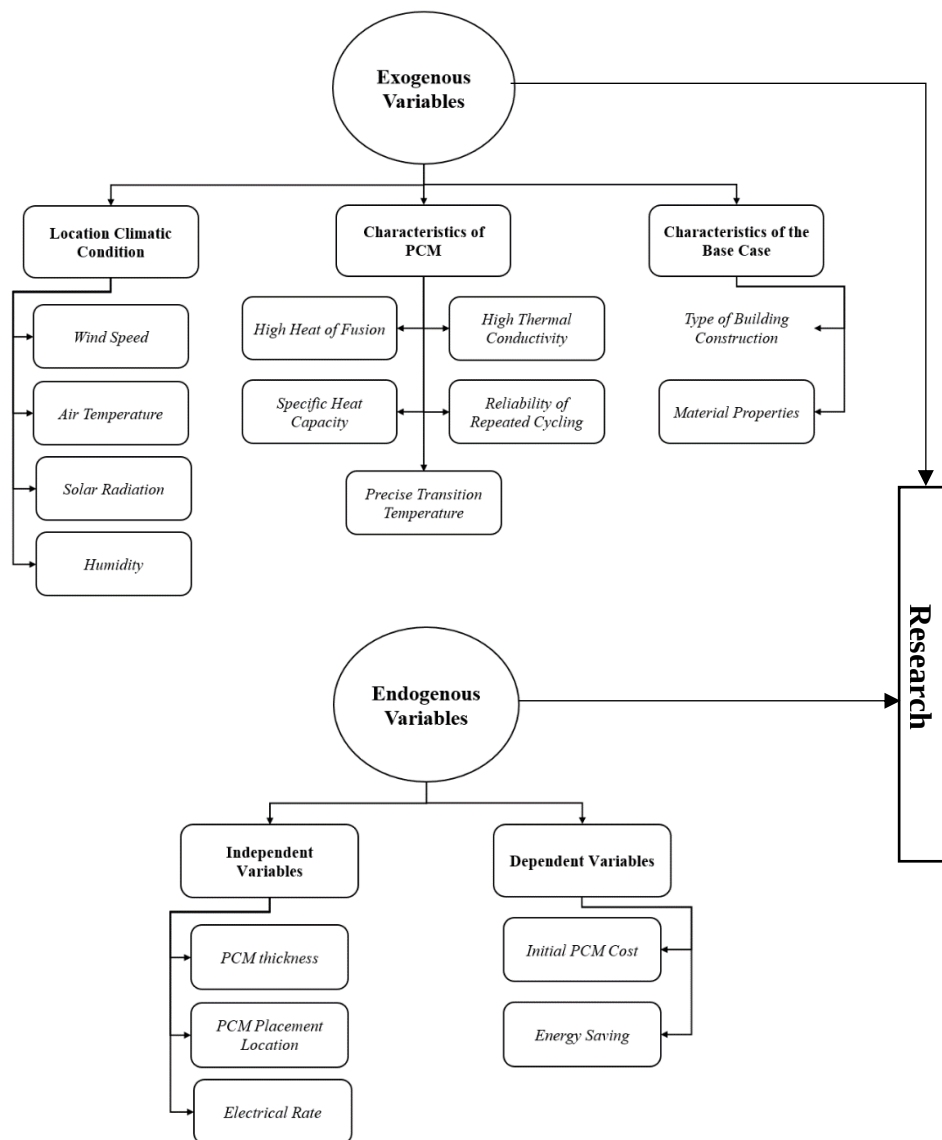


Figure 17. PCM Endogenous & Exogenous Variables.

3.2.1 Exogenous Variables

The first variable to be considered, which impacts the model but is external to the research question, is the location's climatic condition, which includes the impact of the following elements: air temperature averages and ranges, solar radiation, humidity, and wind speed. 1) Air temperature measures how hot or cold the air around an object is and is influenced by natural factors such as latitude, elevation, and distance from the seas, as well as the region's precipitation, which is affected by proximity to mountain ranges and prevailing winds; 2) Solar radiation, representing the energy emitted by the Sun as short waves of radiation, weakens after passing through the atmosphere in the presence of clouds and gas molecules. Once it reaches the oceanic and continental land surface, it gets either absorbed or reflected into outer space in the form of long-wave radiation; 3) Humidity, the amount of water vapor in the air, is formed from water evaporating from lakes and oceans, contributing to higher humidity levels in regions near warm bodies of water, like the Red Sea, the Persian Gulf, and Miami; 4) Wind speed, a measure of air movement, typically arises from temperature variations and atmospheric dynamics.

These four factors combined create a natural heat force on buildings, resulting in heat exchange between the outdoor and indoor environments. The heat exchange occurs through the building envelope through three scientific thermodynamic modes: conduction, convection, and radiation. The variation in air temperature averages, the amount of heat energy received from the Sun (solar radiation), location humidity averages, and wind speed all influence each other, eventually increasing or decreasing the amount of heat force that surrounds the building. Thus, the impact of these factors combined is a considerable exogenous variable.

The second variable to consider is the characteristics of the PCM. PCM exists in various classes, each with its own set of specifications that impact its functionality. Hence, these variables

are crucial when selecting a PCM product. An ideal PCM possesses several key attributes: 1) Latent heat of fusion, or enthalpy of fusion, denotes the amount of heat required to change 1 g of a solid to a liquid at a constant temperature. A high heat of fusion implies that the material necessitates a significant amount of heat to transition between solid and liquid phases at a constant temperature. 2) Thermal conductivity assesses the material's capacity to conduct heat, with materials exhibiting low thermal conductivity transmitting heat more slowly than those with higher conductivity. 3) Specific heat represents the quantity of heat needed to raise the temperature of 1 kg of material by 1 K. 4) PCM has the unique ability to absorb and release thermal energy (heat) during both the melting and freezing processes. This reciprocal phenomenon is known as the thermal cycling process. Effective thermal cycling entails the material melting when it absorbs heat and freezing when it releases heat, all without any change in its composition, ensuring proper PCM function. 5) The transition temperature marks the point at which PCM changes phase, transitioning between liquid and solid states. It liquifies when the temperature surpasses the transition temperature and solidifies when the temperature falls below this threshold.

The selection of PCM depends on its technical specifications that are suitable for the type of application. In our study, 1) A PCM with a high enthalpy of fusion is required to increase the amount of heat absorbed before changing phase, making it suitable for use in hot climates. 2) A PCM with a higher thermal conductivity rate allows for faster heat transmission and a more efficient PCM function in containing transferred heat. 3) PCM with high specific heat enhances the material's ability to withstand high temperatures, making it suitable for hot climates. 4) PCM function is represented by its repeated cycles of changing phase by absorbing and releasing heat. If the cycle is not stable, it can impact the PCM function and reduce its reliability. 5) A suitable

precise transition temperature is essential to match Riyadh's temperature variation and optimize heat transformation.

The third variable concerns the characteristics of the case study, including building type, construction methods, and material properties. These case study characteristics, as illustrated in Table 1, directly impact the model, especially through the physical properties of the materials and the type of construction. The building envelope materials, which deal with heat exchange from the outside, are particularly affected by the thermal performance of other materials, ultimately influencing the application of PCM and its performance.

3.2.2 Endogenous Variables

Endogenous variables are specific to the study and represented by independent variables such as PCM thickness, PCM placement location, and electricity rate: 1) PCM is applied to enhance the thermal performance of the building envelope and delay heat transfer to the interior conditioned space. The research aims to optimize PCM application by determining the ideal thickness since the ability of PCM to absorb and release heat is related to its thickness. 2) The placement location of PCM within the wall should be fitted to the building's location and climate conditions. The research aims to identify the optimal placement location that enables PCM to function effectively and enhances envelope thermal performance by reducing heat transfer. 3) The electricity rate in KSA is the last independent variable considered in our study which will be used later to compare the overall electricity cost savings to the initial cost.

Dependent variables are identified as the initial PCM cost and electricity cost savings. 1) The initial cost of PCM depends on the quantity required to achieve the optimum PCM thickness. The greater the required thickness, the higher the cost. This variable will be determined after establishing the ideal thickness for Riyadh's climate. 2) Overall electricity cost savings depend on

optimizing PCM thickness and placement location. Optimizing PCM applications means achieving the highest thermal performance with maximum energy savings.

3.3 Research Scope

The research study focuses on incorporating PCM into SIPs. The primary goal of this research is to identify the optimum placement and thickness of the PCM within these panels. To achieve this, the study uses a series of simulations and utilizes the data obtained to determine the optimal location and thickness of the PCM. It's worth noting that the research scope focuses on this determination and does not cover the technical aspects of the actual fabrication and installation of PCM into the panels. However, the successful installation of PCM within the panels will heavily rely on the findings from this research. It's important to consider that placing the panels on either the exterior or interior faces is simpler than sandwiching them within the middle of the panels. Therefore, future research should give careful thought to the practical application of these findings.

3.4 Quantitative Tactics

This study aims to investigate, test, modify, and optimize PCM variables through their application in modular housing in KSA. As part of the study design, thirteen models will be compared. The research aimed to employ three main strategies: full-scale installation, laboratory experiments, and energy simulations, each with its limitations and potential obstacles that can impact the study's accuracy and scope. For instance, the full-scale installation alternative would involve a substantial construction period and the setup of monitoring equipment, which would be costly and time-consuming for thirteen models over an entire year. It would also necessitate a dedicated space to prevent any unexpected interventions that might affect the study. However, this approach might lack external validity, as it moves from real-life settings to controlled conditions,

potentially influencing the outcomes. Therefore, the research will primarily utilize energy simulation as a strategic approach.

3.4.1 Energy Simulation Tactic

Computer simulations have commonly been used in science and building energy modeling. The central epistemological question addresses the conceptual role that computer simulations should play in theoretical work and experimentation on the methodological map (Jebeile, 2017). Humphreys proposed that computational methods of numerical investigation present a new kind of scientific method, situated between empirical experimentation and analytical theory (1994). Computer simulations serve unique epistemic functions alongside experimentation as they are capable of obtaining new and complex data that cannot be acquired or examined using typical instruments (Barberousse, Franceschelli, & Imbert, 2008). Some researchers have recently recognized similarities between simulations and experiments, acknowledging the advantages of substituting or complementing experimentation with computer simulations in terms of cost, time, politics, and when certain aspects of experimentation are deemed unacceptable or unethical. When lab experiments are replaced by simulations, as in this study, the simulations are referred to as numerical experiments, experimental simulations, and simulated experiments (Humphreys, 2007). Moreover, Jebeile further expounded on the assertion that computer simulations can generate innovative knowledge about the empirical world, similar to experiments. He concluded that 'simulations and experiments generally yield new knowledge under the same epistemic circumstances, regardless of the features they may share. This is a way of making sense of the novelty claim. They provide new knowledge when obtained first and expand the existing knowledge base' (Jebeile, 2017).

3.4.1.1 Simulation Software Selection

Energy modeling is a relatively new technology utilized for the last two decades. It is an essential emerging technology and a practical tool now used in the early design phase or building retrofits. While many highly reliable software applications used in the industry have energy modeling as a core function, some applications, such as EnergyPlus (E+), have advanced methods and features that are compatible with new building industry applications and methods.

E+ (Fig. 18) is a whole-building energy simulation program that models the entire energy system of a proposed building and is now one of the most widely used energy modeling programs in the industry. The software represents a new era of building energy simulation programs based on the Basic Local Alignment Search Tool (BLAST) algorithm and DOE-2 building energy modeling. Moreover, it is provided to users at no cost since it is open-source software offered by the Department of Energy.



Figure 18. E+ software (EnergyPlus, 2022).

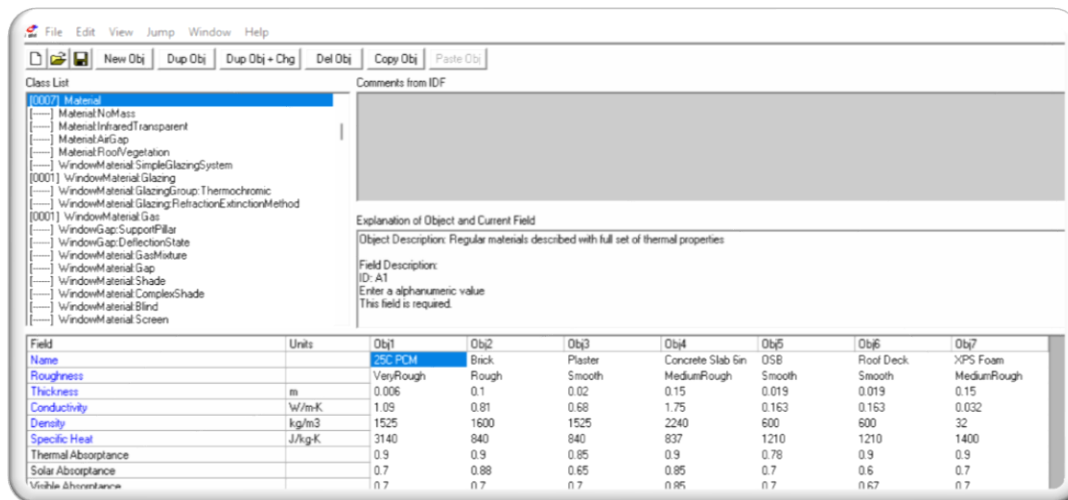
E+ is optimal for its reliability, and it is one of the few tools that can simulate PCM materials. In recent years, significant efforts have been made to add and enhance the feature of

simulating PCMs. E+ uses heat conduction transfer functions to simulate the building surfaces, which are based on constant, continuous properties and fixed values of certain parameters. However, these did not produce results for the surface interior as required for PCM simulation; therefore, E+ developers implemented the conduction finite difference (CondFD) solution algorithm to properly simulate PCM heat transfer.

Zhuang et al., Sang et al., and Wijesuriya et al. studies have verified E+'s accuracy and validity. These studies compared E+ simulation results to experimental case studies where sensors and monitors were used to calculate heat transfer and measure indoor temperature variation. This approach allowed researchers to compare the results and calculate the average difference between the experiment and its simulation. Zhuang et al.'s 2010 study found that the comparative results corresponded, suggesting that E+ can simulate the heat transfer conduction through PCM wall structure and the indoor air temperature in light weigh building. Another study (Sang et al., 2017) used the same methodology and corroborated these findings. The study stated that the data obtained from E+ was able to capture the trend of the walls inner surface temperature variation. Moreover, E+ was tested and compared with other simulation software, The study used experimental data from two former PCM studies and compared the PCM models implemented in different energy modeling software. E+ is one of the empirical building energy software used. The study states the following in its conclusion: “This study affirms that these numerical modeling software can be used to model PCMs and extend the studies to evaluate unique behaviors like hygrothermal performance (WUFI, EnergyPlus).” (Wijesuriya et al., 2020).

E+ utilizes fundamental principles of heat transfer and thermodynamics, which include conduction, convection, and radiation, to simulate the thermal performance of building enclosures. For accurate simulations, specific physical properties and configuration inputs related to the

materials used in the building envelope are essential (Fig. 19). The simulation utilizes the input from the material physical properties to calculate the heat transfer through the wall from the outside to the inside, considering such as absorbed solar radiation, long-wavelength radiation exchange, and convective flux with the outside air (Fig. 20).



Field	Units	Obj1	Obj2	Obj3	Obj4	Obj5	Obj6	Obj7
Name		2SC PCM	Brick	Plaster	Concrete Slab 6in	OSB	Roof Deck	XPS Foam
Roughness		VeryRough	Rough	Smooth	MediumRough	Smooth	Smooth	MediumRough
Thickness	m	0.006	0.1	0.02	0.15	0.019	0.019	0.15
Conductivity	W/m-K	1.09	0.81	0.68	1.75	0.163	0.163	0.032
Density	kg/m3	1525	1600	1525	2240	600	600	32
Specific Heat	J/kg-K	3140	840	840	837	1210	1210	1400
Thermal Absorptance		0.9	0.9	0.85	0.9	0.78	0.9	0.9
Solar Absorptance		0.7	0.88	0.65	0.85	0.7	0.6	0.7
Visible Absorptance		0.7	0.7	0.7	0.85	0.7	0.67	0.7

Figure 19. Material Properties Class Inputs E+

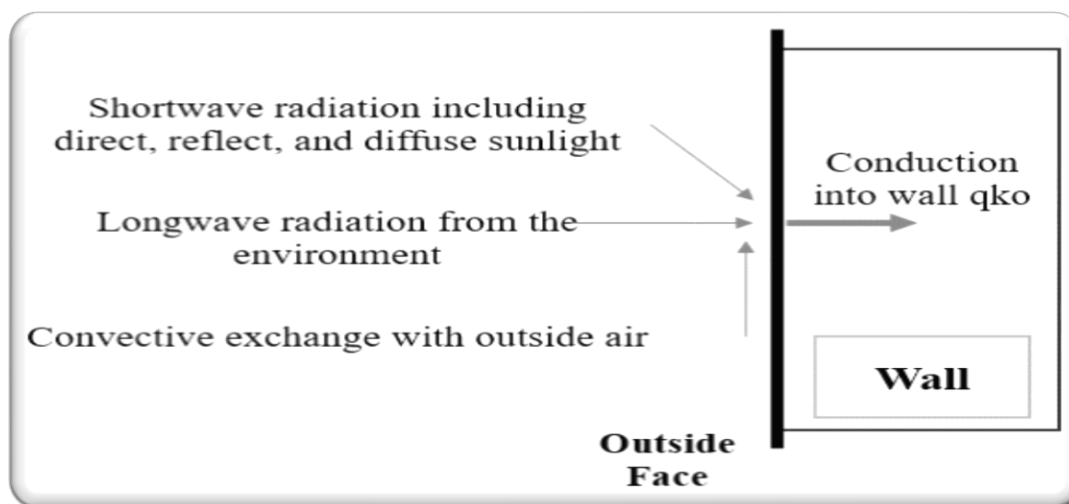


Figure 20. Exterior wall heat sources (big ladder software).

E+ calculates the heat transfer through the application of the Conduction Transfer Function (CTF) method. The method uses a single linear equation with persistent coefficients that link heat flux on building surfaces to exterior and interior surface temperatures and past heat flux readings on the inner surface. The CTF method doesn't need to calculate material internal temperatures which makes it applicable to various surface types. (EnergyPlus, 2024).

The CTF Method is limited to constant material properties and fixed parameter values due to its inapplicability to materials with internal heat. With the need to advance energy simulation tools to meet the industry demands and accommodate emerging advanced materials in the construction industry's material such as PCM. The conduction finite difference algorithm has been created and integrated into E+ to meet these needs. However, CondFD is not a substitute for the CTF solution; rather, it complements it, particularly in cases involving PCM or materials with variable thermal conductivity (EnergyPlus, 2024).

The behavior of PCM is calculated in E+ by capturing the energy changes that occur during phase transitions. E+ ensures the simulation presents the behavior of the material as it heats up and cools down by developing a relationship between the material's temperature and its total energy content. E+ has a method that divides the heat conduction process over both time and space to ensure the stability and accuracy of the simulation. Iterative upgrades are applied to improve the PCM calculations. The program continuously modifies the temperature at each step until the results match, guaranteeing accurate and reliable results. E+ has the flexibility for multiple simulation input settings, the user selects the number of iterations and convergence criteria. This guarantees the modeling of PCM behavior and enables modifications to suit particular requirements. The heat exchange for the material surface is also taken into account through the application of a comprehensive model of thermal radiation which eventually leads to the creation

of a realistic simulation environment. In addition, E+ models hysteresis effects to add the capability for the simulation of PCMs hysteresis as they transit between melting and freezing points (EnergyPlus, 2024). Hysteresis is important in PCM simulations because it reflects the material's thermal behavior during phase transitions, specifically between melting and freezing.

Finally, the software allows users to adjust the level of detail in the simulation. By influencing how finely the material is divided for analysis, users can control the spatial resolution, enhancing the precision of the simulation. Additionally, E+ combines energy-temperature relationships, stable simulation methods, iterative updates, customizable settings, thermal radiation modeling, hysteresis effects, and flexible spatial resolution to accurately simulate the behavior of Phase Change Materials.

3.4.1.2 Case Study Tactic Argument

Yin (2014) defines a case study as “an empirical inquiry that investigates a contemporary phenomenon within its real-life context.” According to De Souza (2015), when a researcher analyzes a specific phenomenon by using a case study method, it provides the study with holistic and meaningful characteristics of real-life events. In addition, the case study method allows the researcher to convert theoretical ideas into realistic objectives.

There are three case study types: explanatory, descriptive, and exploratory. The explanatory type has two aims: 1) revealing how and why a series of events occurred, and 2) introducing data's bearing upon cause-effect relationships. The exploratory type characterizes the questions and speculations of a consequent study or decides the achievability of the required investigation strategy. The descriptive type “presets a complete description of a phenomenon within its context” (Yin, 2014). It usually involves hypotheses formatting of cause-effect relationships. The explanatory case study type is most suitable for the current research objectives.

It will facilitate the investigation of PCM application through the identified variables' relationship and impact on each other, and it will frame the outcomes in the LCCA to answer the main research question.

3.4.1.3 Case Study Selection & Specifications

This research is conducted in collaboration with the King Abdulaziz City for Science and Technology (KACST) housing project, which investigates the use of the modular housing approach to address the challenges related to housing construction and performance in KSA. The project includes six types of modular villas in Riyadh and proposes using structural insulated panels (SIPs)—a high-performance system for lightweight construction. Our study will utilize one villa as the research base case (Fig. 21), and in collaboration with KACST, will investigate the application of PCM outcomes and LCCA considerations in modular housing in KSA.

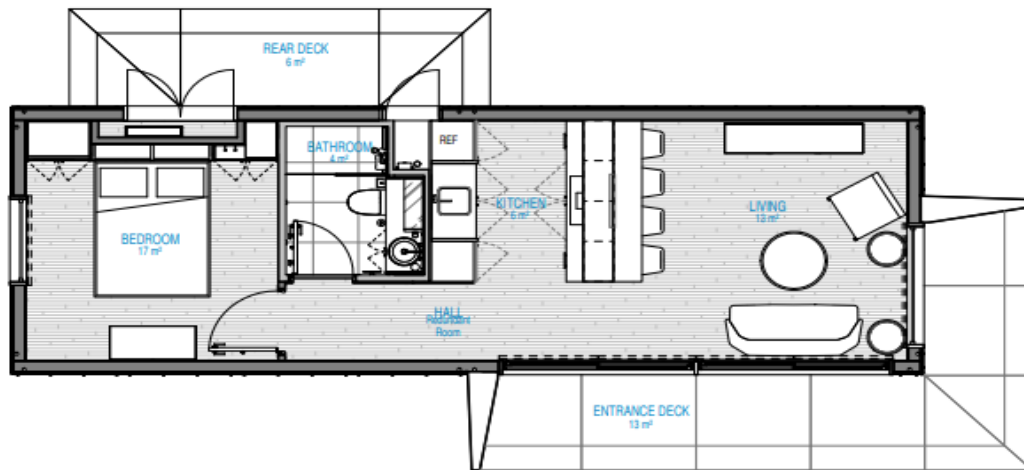


Figure 21. KACST Modular Villa (KACST Representer, 2022).

The project climate conditions are an essential factor in investigating the application of PCM because it determines the selection of the PCM type and transition temperature. KSA has six different climate zones, and the temperatures vary from zone to zone depending on the geographical conditions. The study will focus on the hot desert climate zone, which covers a significant portion of the country, specifically the central and eastern regions. The study base case

is located in Saudi Arabia, Riyadh, in the Nafud desert (World Population Review, 2023). Riyadh is one of the most populated cities in the Middle East and is currently facing massive industrial and business development as part of the country's Vision 2030. The intention is to increase the city's population from 15 million to 20 million within six years. Addressing housing needs and accommodating the rapid population growth, the government has announced 23 housing projects that are planned to be developed in a short period. This in turn creates a need to investigate solutions to solve the energy consumption dilemma and meet the construction demand. Additionally, the study is collaborating with KACST on their mega project planned with it high volume of 5000 units annually, which will be located in the capital city Riyadh, which has the same aim to address the high demand for construction and improve thermal performance efficiency.

3.4.1.4 Base Case Characteristics and Variants

For this study to obtain accurate outcomes, the case study's descriptive characteristics and specifications must be accurate inputs for the E+ simulation. The villa's detailed specifications were obtained for the case study. Additionally, the researcher drew from architecture and building science experience to add or assume salient points. The following table displays the specific characteristics of the base case (Table 2) and the key assumptions that will be implemented in the simulation. The only variation that will occur in the enclosed walls will be the incorporation of PCM with different thicknesses and placements within the wall, as illustrated in (Fig. 22), to determine the optimum thickness and placement that will produce the highest energy savings in the model. The figure describes the study samples. Sample A does not contain PCM, while groups (B, C, and D) are the groups that incorporate PCM with different thicknesses and locations. Group

B has PCM as the second layer from the outside to the inside with four different thicknesses, Group C has PCM in the middle of the wall with four different thicknesses, and Group D has PCM as the second layer from the inside to the outside with four different thicknesses. The designated thicknesses for each group are also provided.

Table 2. Base Case Specifications.

Specifications of KACST Villa for E+ inputs	
Villa Location	KSA, Riyadh City.
The size of the villa	The total size of the building (Length × Width × Height) (12×3.9×3.2) = 151 M ³ / (39.7×12.9×10.4) = 497 ft ³ .
Floor Area	(Living room 13 m ² (42ft ²) - Bedroom 17 m ² (55ft ²) - Kitchen 13.4 m ² (44ft ²) - Bathroom 4 m ² (13ft ²) / Total = 47.4 m ² (512ft ²).
Foundation	15 cm (6") Slab Foundation.
Floors	10 cm (4") SIPs Floor.
Walls	20 cm (8") SIPs.
Windows	- Living room (1.3×1.2m) (4.2×6.5ft). - Bedroom (1.8×1.2m) (5.9×6.5ft). High-performance windows with 0.3 U-Factor and 0.32 SHGC.
Doors	Glass Doors 2.2×2.
HVAC	Split units in each zone.
Set points	Summer Season 75 °F (24°C) – Winter Season 65 °F (18°C).
Lighting	14 LED Lights.
Equipment	(Electrical stove, Fridge/Freezer, Microwave, Dishwasher, Washing machine, Water heater).
Occupants	2- 4 People.

The application of external cladding materials is dependent upon the construction type and function, while there are a wide range of materials available. Reporting on all possibilities is beyond the scope of this study. The primary focus is on testing the thermal performance of the

core SIPs construction integrated with PCM. Comparatively, common materials, such as brick, concrete, and magnesium possess a relatively low calculated R-value compared to the SIPs core:

- **2 cm Brick Cladding:** R-value = $0.025 \text{ W/m}^2\cdot\text{K}$.
- **2 cm Concrete Cladding:** R-value = $0.014 \text{ W/m}^2\cdot\text{K}$.
- **1.2 cm Magnesium Board:** R-value = $0.0077 \text{ W/m}^2\cdot\text{K}$.

The overall R-values with these claddings are only slightly higher than the SIPs core alone:

- **SIPs Panels:** R-value $6.79 \text{ W/m}^2\cdot\text{K}$.
- **SIPs with 2 cm Brick Cladding:** R-value = $6.81 \text{ W/m}^2\cdot\text{K}$.
- **SIPs with 2 cm Concrete Cladding:** R-value = $6.80 \text{ W/m}^2\cdot\text{K}$.
- **SIPs with 1.2 cm Magnesium Board:** R-value = $6.79 \text{ W/m}^2\cdot\text{K}$.

While these external materials have a minimal impact on thermal performance, future research could explore the effects of assorted cladding options using the equivalent methodology and testing approach.

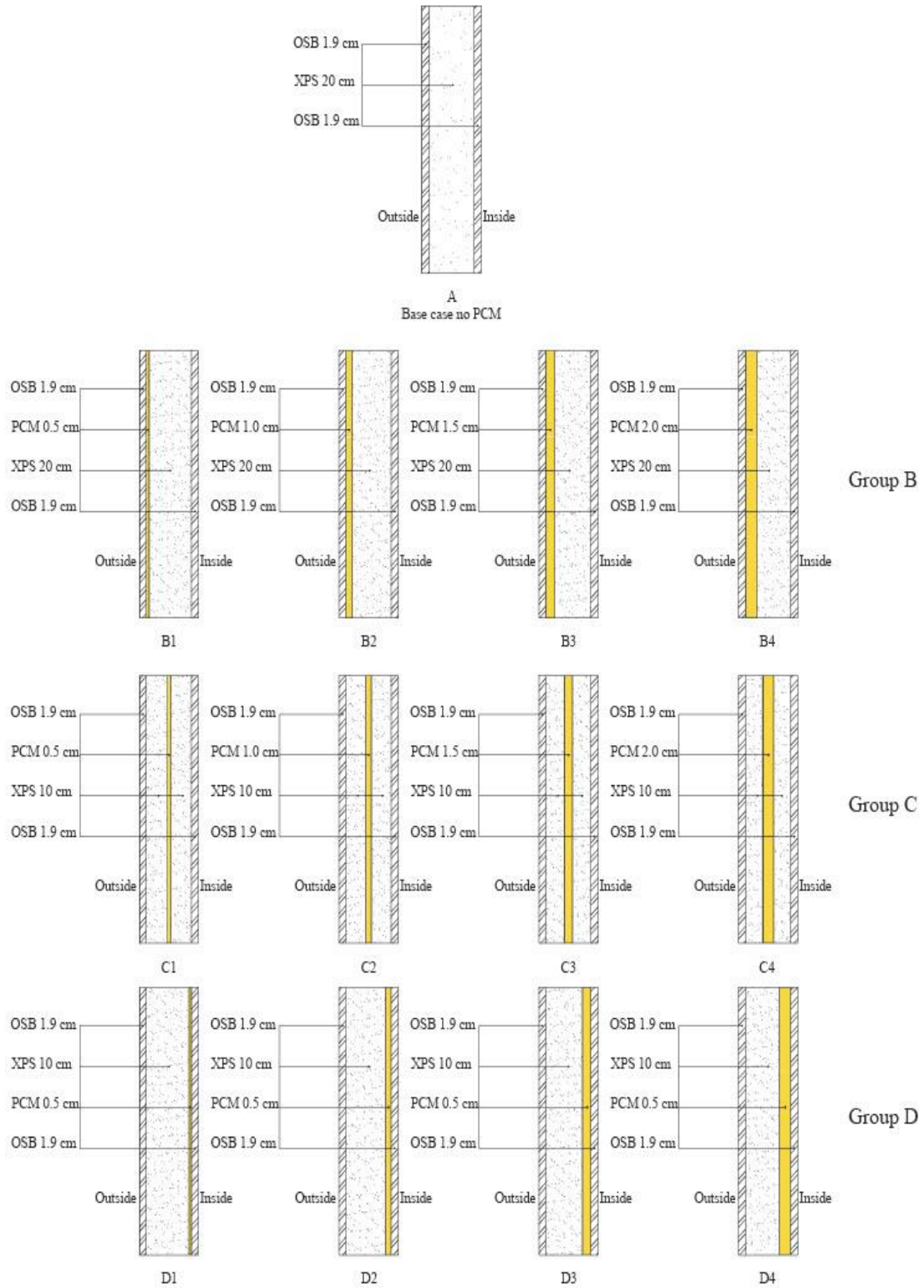


Figure 22. PCM Locations & Thicknesses Proposed.

3.4.1.5 Energy Modeling Scope and Boundaries

To ensure the accuracy of the study outcomes, a base case simulation was developed to simulate real-life data. The input data for the simulation includes the following:

- Temporal: In order to obtain the necessary data for the study, the base case will collect energy performance data for a complete year, including all four seasons. The data will be collected and analyzed at a daily level and monthly with the data sourced from 2024.
- Spatial: The base case unit is divided into three zones that will be input into E+. Two of these zones are conditioned, while one is non-conditioned. Zone A is the living room and open kitchen area, with a volume of 60 cubic meters. Zone B is the bedroom, with a volume of 54.4 cubic meters. The final zone, C, is the bathroom with a volume of 12.8 cubic meters.
- Space Utilization: Zone A is designated as a family living space, with activities that include kitchen utilization. Zone B is designated as a family sleeping and rest space. The utilization schedule input into E+ takes into consideration the allocation of space utilization.

3.5 Phase Change Material Selection

The widespread use of PCM in the industry has led to the development of different approaches and application techniques to optimize PCM performance, maximize its benefits, and minimize its drawbacks. Moreover, the demand for PCM application has made industry producers extremely competitive. As such, companies have developed various products with specialty mixes of PCM, different methods of capsulation, and wide ranges of specified or customized melting points according to clients' needs.

The selection of PCM began by considering the literature recommendations for choosing phase change materials (PCMs) for building envelope applications to optimize their function and increase energy savings. PCM melting points should be chosen based on the specific site location,

taking into account the climatic conditions and diurnal temperature variations (Sari, 2014). In addition, the selected PCM should have high latent heat per unit volume, high heat capacity, high conductivity for rapid response, and chemical stability and durability (Barreneche et al., 2014). Thus, three products were identified with different transition temperatures suitable for the study location (Fig. 23, 24, and 25). The second objective was to ensure that these three products meet the literature recommendations for high latent heat per unit volume, heat capacity, chemical stability, durability, and high conductivity.



Figure 23. Templok (Source:InsolCorp)



Figure 24. ENRG Blanket (HTS, 2022)



Figure 25. ENRG Blanket (greenworldtek).

The three products share similar specifications with only slight variations in their transition temperatures, as indicated on their respective company websites (refer to the specifications attachment). However, Templok was chosen over the other two products since they have minor differences in transition temperatures but more flexibility in size customization, which will be more suitable for our type of research (Table 3). In addition, the company already has four thicknesses and two-panel sizes as standards. According to Peter Horwath, the company CEO, the company offers customization options for an additional fee, and for larger projects, they may even cover the costs.

Table 3. TEMPLOK (Insolcorp, 2022).

PCM Technical Specifications	
Thermal capacity	100 btu/sf.
PCM Material	Mineral-based/ Inorganic.
Transition temperatures	22 °C, 25 °C, and 29 °C.
Dimension	Standard 16" & 24" wide x 24", 48", and 96" long.
Latent Heat	86 btu/lb.
Specific Heat	1.35 btu/lb°F.
Thermal Conductivity	~ 0.16 W/ft/k Liquid) (~ 0.33 W/ft/k Solid).
Thickness & weight	0.25" thick; 1.1 lbs./sf (+/-).
Flame spread	ASTEM 84 UL 723 - Flame 5, Smoke 10.
Permeability	ASTEM 96 - 0.08 (grains/hr.*ft ² inHg).

The selection of the PCM transition temperature significantly impacts the study results and the TEMPLOK product comes with three different temperatures: 22 °C, 25 °C, and 29 °C. Therefore, to determine the applicable transition temperature to Riyadh, KSA's climate in this study, preliminary simulations were performed using TEMPLOK with three different temperatures to determine which temperature yields the best performance. The overall study utilized seven data comparison metrics, explained in the coming data comparison metric section, but one is the total site energy that gives the highest overall energy savings when compared to the base case.

The simulation result of the base case with PCM 22 °C incorporated had a total site energy of 104.27 [GJ] which resulted in a saving average of 0.5% when compared to the base case (Fig. 26). The saving breakdown has shown a reduction in the cooling and heating energy by 5.7%. The second temperature of 25 °C of PCM transition results, had giving a better total reduction of the site energy of 0.6% resulting from a minor reduction in the total cooling and heating energy. In the third transition temperature applied, the temperature of 29 °C application provided a lower saving average of 0.3% when compared to the two previously suggested temperatures.

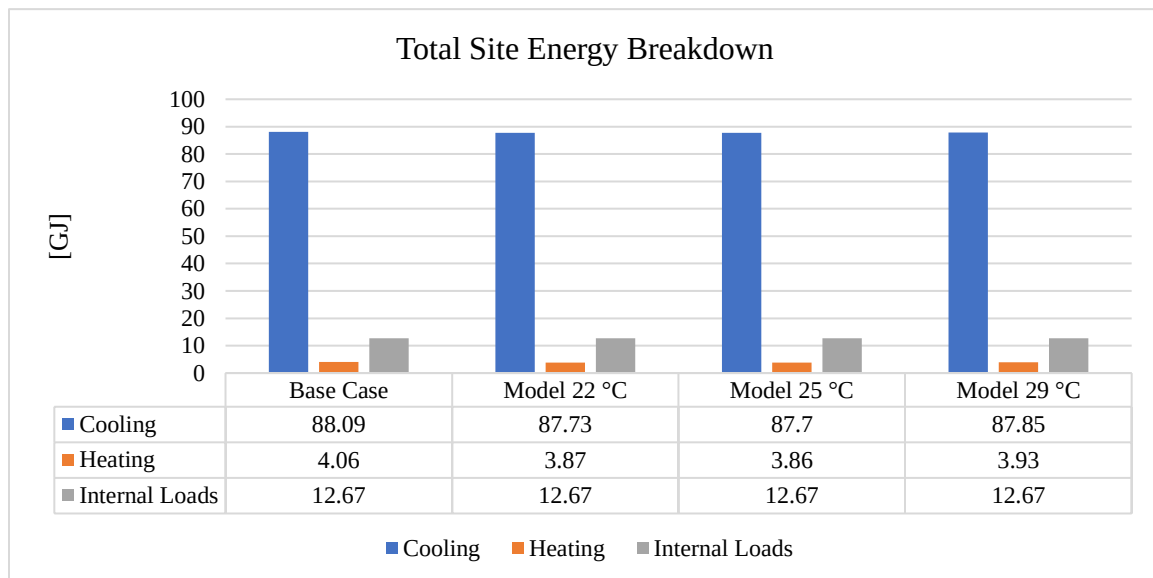


Figure 26. Simulation Results of the Suggested Transition Temperatures.

The initial simulation results aim to determine which transition temperature should be utilized in our study. The application of PCM is very unique and transition temperature selection depends on the project location condition. The simulation results have shown minor changes in the total site energy and demonstrate the impact of the PCM application. However, based on the energy savings obtained in the simulation, the results have shown that the selected transition temperature in our research will be 25 °C according to the results since it has the highest energy reduction among other transition temperatures (Fig. 27).

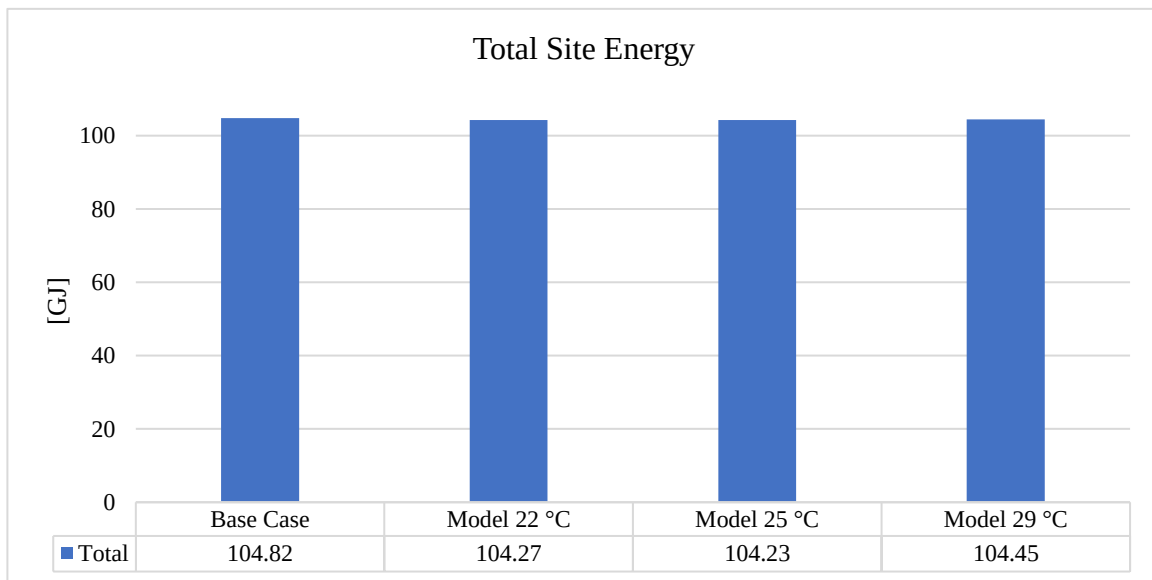


Figure 27. Simulation Results of PCM Application with Suggested Transition Temperatures.

3.6 Simulation Context & PCM Application

The simulation consists of two main phases, the outcomes of which form the basis for the Life Cycle Cost Analysis (LCCA) in Phase Three. Phase One aims to develop the initial model of the KACST villa as a case study with no Phase Change Material (PCM) in E+; this will serve as the baseline model (A) for the entire research (Fig. 22). Phase Two will determine the optimal thickness and location of the PCM by obtaining the best performance results. This phase involves three models (B, C, and D). These models will each expand into their respective groups:

Group 1: PCM applied as the second layer from the outside face with different thicknesses (B1 - 0.5 cm, B2 - 1.0 cm, B3 - 1.5 cm, B4 - 2.0 cm).

Group 2: PCM applied in the middle within the wall with different thicknesses (C1 - 0.5 cm, C2 - 1.0 cm, C3 - 1.5 cm, C4 - 2.0 cm).

Group 3: PCM applied as the second layer from the interior face with different thicknesses (D1 - 0.5 cm, D2 - 1.0 cm, D3 - 1.5 cm, D4 - 2.0 cm) (Fig. 22).

The thickness and location of insulation and thermal mass material based on climate and building type because different conditions and usage patterns influence how buildings gain and lose heat. The main function of insulation in hot climates is to prevent heat from entering the building, so thicker insulation is often placed on the exterior side to reduce solar heat gain. In contrast to cold climates, insulation is typically installed from inside walls to retain heat generated indoors, which requires more thickness to prevent heat loss. In regions with both hot summers and cold winters as in our case, insulation is carefully balanced in terms of thickness and placement to regulate heat flow in both directions, ensuring energy efficiency year-round.

The research plan organizes the model groups to assess the performance of PCM in all locations with different thicknesses, covering all possibilities for better optimization. The simulation results from all the models were compared to the base case to determine the optimum thickness and location for PCM. Additionally, the analysis included the total initial cost and energy-saving variables (Fig. 28).

Phase Three involved the structure and conduct the LCCA, which requires the initial cost of the PCM and overall energy-saving variables. The initial cost and energy-saving variables were acquired from the optimal model that showed the highest performance during the simulation series.

The LCCA approach and other required variables were identified and explained in detail in a later section (Fig. 29).

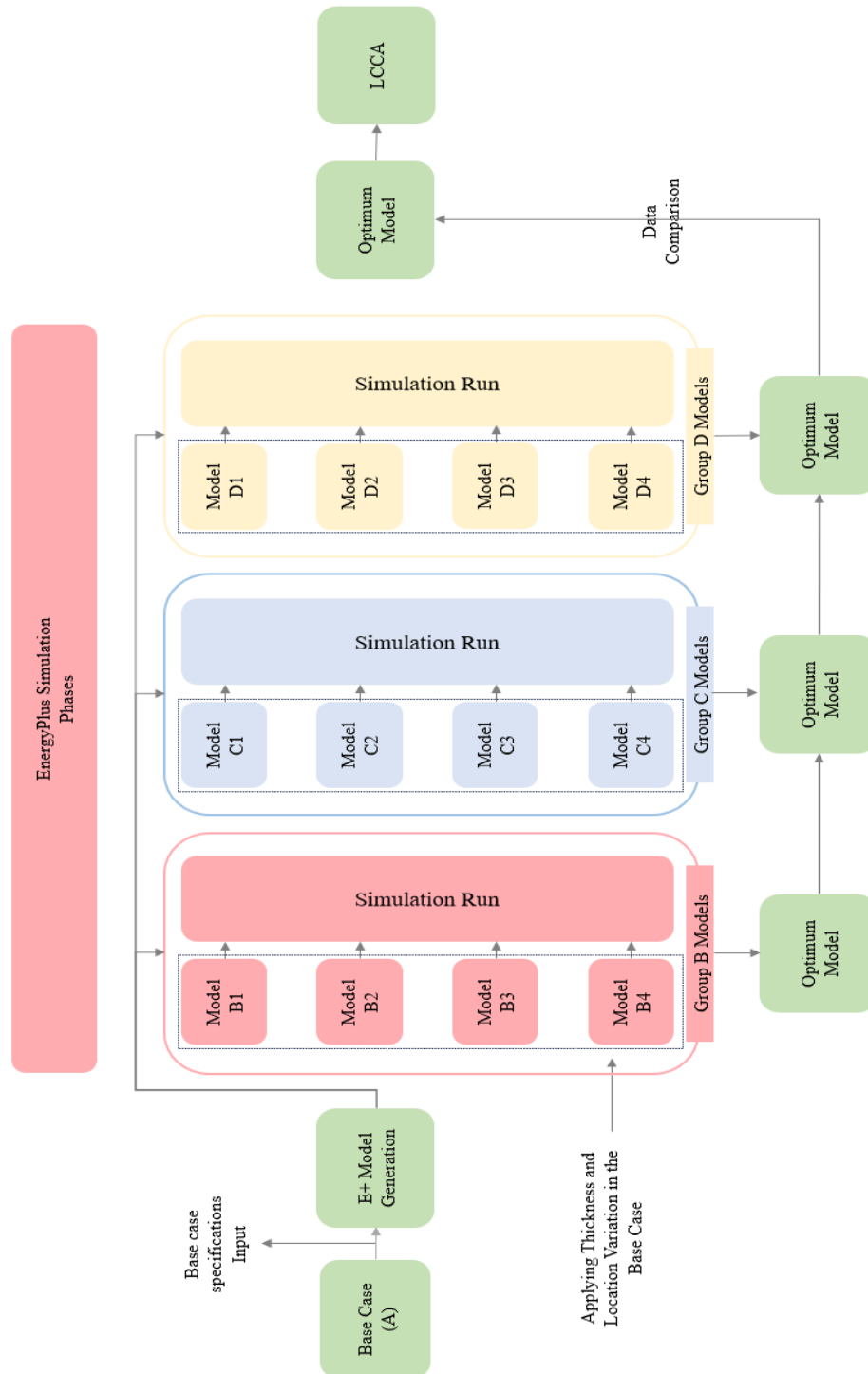


Figure 28. Simulation Context.

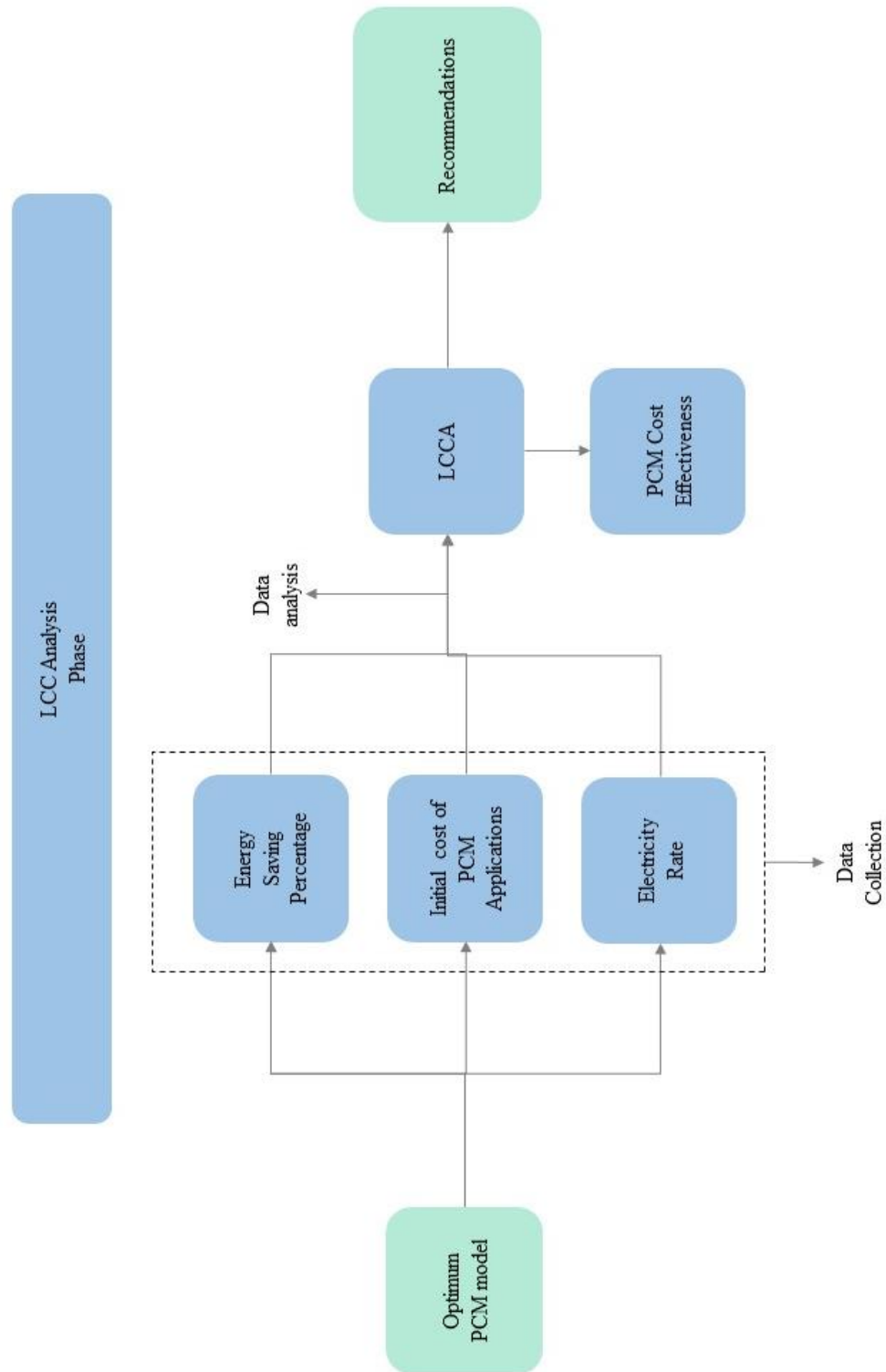


Figure 29. LCCA Phase.

3.7 Optimization Criteria and Metrics

This study aims to determine the most efficient thermal performance of building walls by introducing phase change materials (PCM) to minimize heat transfer to indoor conditioned spaces and assess its impact on the HVAC system and overall energy consumption. The study monitoring criteria was based on three factors: average heat transfer, HVAC utilization, and total energy consumption. To evaluate the effectiveness of the PCM, E+ generated quantitative reports on the building elements and systems' performance. Seven types of reports, as listed in (Table 4), were used as study metrics to provide a visual representation of the data and facilitate comparison by focusing on the total site energy.

Table 4. E+ Utilized Reports Description (big ladder software, 2022).

No.	Report Type	Description
1	Outdoor air dry-bulb temperature	
2	Zone Air Temperature	
3	Surface Average Face Conduction Heat Transfer Rate [W]	These “average face conduction” output variables combine the inside face conduction and outside face conduction reports to describe the conduction situation in a heat transfer surface nominally. This is simply the average of the inside and outside face conduction rates, but with the sign convention for the outside face switched to match the inside face positive values here indicate heat flowing into the thermal zone.
4	Surface Average Face Conduction Heat Loss Rate [W]	
5	Zone Ideal Loads Zone Total Cooling Rate	The total (sensible and latent) cooling energy (or rate) removed from the zone.
6	Zone Ideal Loads Zone Total Heating Rate	The total (sensible and latent) heating energy (or rate) added to the zone
7	Total Site Energy	Total Site Energy is the “gross” energy consumed by the building site
*Zone Air System Sensible Heating & Cooling Energy reports the heating or cooling delivered by the HVAC system to a zone.		
*The basic heat conduction rate (W) Positive value indicates heat flowing toward the thermal zone.		

3.8 Optimization - Weighting of the Parameters

Optimization typically involves multiple parameters that require the weighting of the parameters to determine the best option. In our case, our optimization involves seven parameters: PCM thickness, PCM location, energy savings, PCM cost, PCM installation cost, total initial cost, and electricity rate. The study's objective is to enhance the thermal performance of the building enclosure walls by optimizing PCM utilization through thermal performance reflected as energy saving and seeking cost-effectiveness. The cost-effectiveness of PCM applications cannot be realistically investigated without optimizing the outcome of PCM performance savings and the initial cost of PCM applications. Cost is a critical factor for decision-making in construction projects, which is given the highest priority in our project. Still, the study aims to investigate the limitations of PCM application by covering all possible scenarios that could be applied, which require giving priority to PCM optimization in the first phase. In the LCCA phase, the priority of cost was considered to provide the limitation applied under all options in the simulation series. The study outcomes provide full insight into the application of PCM in terms of performance and cost, offering strong input for decision-making in the industry. Therefore, the study focuses first on optimizing PCM's performance, represented by the highest energy savings from PCM application, which were used as a variable in the next phase of the research.

The optimum performance of PCM in the envelope depends on optimizing two variables: the placement of PCM, whether it is from the inside to the outside or vice versa, and the thickness of PCM implemented. Optimizing the thickness and location impact was reflected as a percentage increase in the parameter of energy savings, which carries the highest weight in our optimization process. While optimizing the location and thickness variables there were two other parameters that were affected by an increase in their values: the cost of PCM installation and PCM cost, which

will eventually contribute to the initial cost value. The study gives priority to optimizing the energy-saving parameter, represented by obtaining the highest saving percentage, without considering the effect that optimization has on other variables until the energy-saving parameter is optimized, especially the initial cost variables (Fig 30).

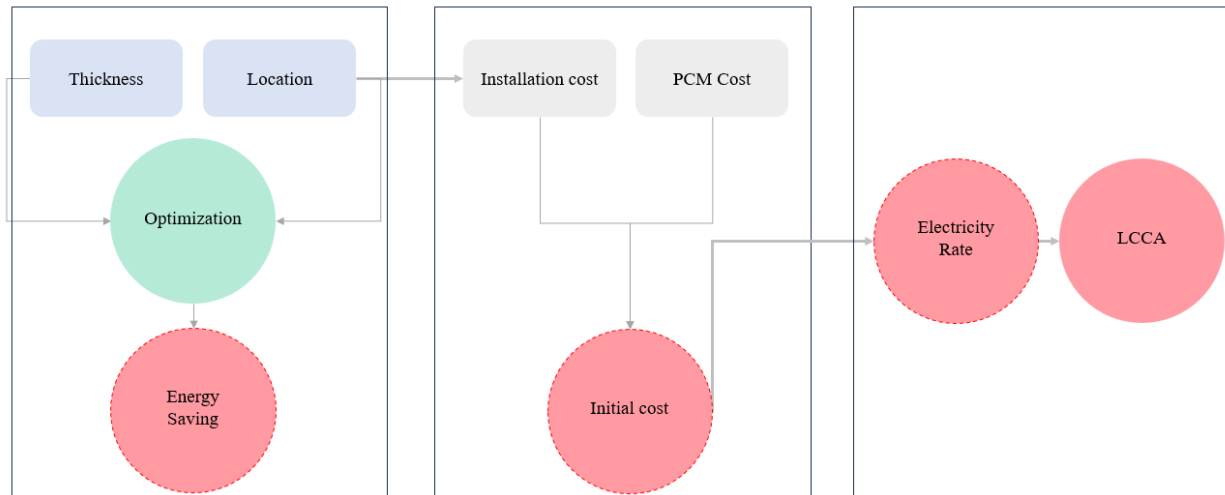


Figure 30. Optimization Parameters.

The initial cost was considered once the optimal model was identified, and the initial cost variable was used as an input in the next stage of the research, along with the parameters of electricity rate and energy saving in the LCCA phase. These three parameters were used to build the LCCA structure as variables. According to the LCCA analysis, the research provides recommendations to the industry about adjusting the cost of PCM installation or manufacturing due to its significant benefits on the building enclosure performance when it's optimized.

3.9 Initial Cost

To determine the initial upfront costs for the enclosure and the PCM, a systematic approach will be followed through the following phases (Fig. 31):

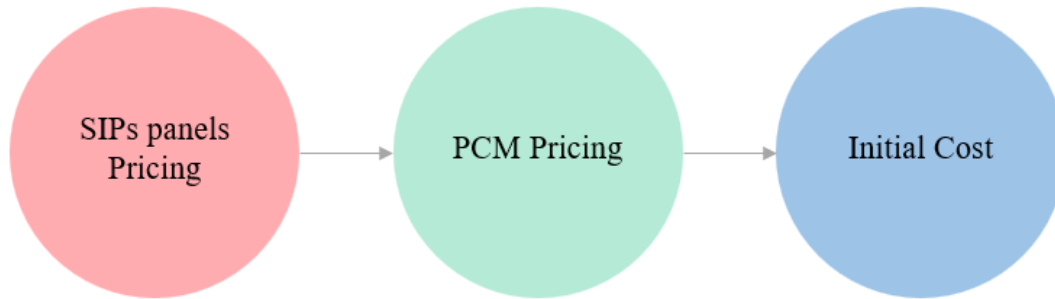


Figure 31. Initial Cost Determination Phases

First, it started with SIPs pricing. The project involved selecting the appropriate size and type of SIPs to be used. To obtain accurate pricing information, I established contact with manufacturers or suppliers to acquire an accurate pricing estimation per square foot. Additionally, labor costs for the installation of SIPs per square foot were considered. The total cost for SIPs per square foot was calculated, taking into account both material and labor costs.

Second, determining PCM pricing. The initial step in determining PCM pricing involves using the research outcomes of the optimum thickness and size of PCM required for the project. As the research considered Templok panels to be used, we assessed whether customization is necessary to ensure compatibility with the selected SIPs type. Price estimates were obtained by reaching out to manufacturers to obtain the cost of PCM. Furthermore, labor costs for PCM installation per square foot were considered, or discussions were held with panel manufacturers to potentially include PCM installation within their pricing structure. The total cost of PCM per square foot was calculated, incorporating material and potential labor costs.

Initial Cost: The final step involves calculating the initial cost, which was the sum of the cost of SIPs and the cost of PCM, multiplied by the total wall square footage. This calculation provided an estimate of the upfront expenses associated with the enclosure and PCM integration.

3.10 LCCA Phase

In the LCCA phase, the application of PCM as an investment in Riyadh, KSA construction was analyzed. The goal was to determine if PCM is a cost-effective investment and to find a baseline for the PCM manufacturing costs to be competitive in KSA. The variables used in this stage are the overall savings percentage of electrical use obtained from the simulation phase, the initial cost of applying PCM, and the current electrical rates in Saudi Arabia. This stage aims to use the relationships between the variables to find the outcomes of implementing PCM. The electrical savings were projected annually to find the period of years in which PCM initial costs would be recouped; this insight into the initial cost compared to the annual savings will attract homeowners to utilize PCM as an investment. Moreover, it will provide a baseline of PCM manufacturing costs for companies in the industry to compete and clarify investment potential for users by establishing the product as a reliable material with a desirable price.

3.10.1 LCCA Example

The following example is based on an assumption made by the author to illustrate the process of the LCCA phase:

- 1- The optimal model from the E+ simulation resulted in 30% annual energy savings on building electricity.
- 2- The initial cost of utilizing PCM in the villa varies according to the thickness from 20,000 SAR - to 30,000 SAR - to 40,000 SAR.
- 3- KSA's electricity rate is (0.18 SAR) per kWh.

- 4- The base case villa consumption range is 2,500 kWh (monthly cost: 450 SAR) to 30,000 kWh (annual cost: 5,400 SAR).

The first step in developing the LCCA chart (Fig. 32) is to represent averages of initial cost as fixed lines (gray lines). The second step calculates the 30% saving of $(5,400) = 1,620$ SAR annual savings. The third step adds the annual savings to the chart as a cumulative line extended through the years (dashed red line) until it intersects with one of the fixed lines of the initial cost. This interaction indicates that the initial cost was paid in the intersecting year axis, and the savings in the following years will become cash savings.

Three variables comprise the sum of initial cost: the market cost to purchase PCM, installation cost, and the cost of increasing the PCM thickness to optimize thermal performance. As the initial cost increases, more years are required for the energy saving obtained from utilizing PCM to payback the initial cost; for example, if initial costs are above 20K SAR, at least 12 years will be needed to break even. Therefore, the market price is a critical factor in utilizing PCM. In another example, if we assume that PCM cost was cheap and the total initial cost sum is between 6K to 10K SAR, then the initial cost would be returned in a time frame of 1 to 5 years maximum (Fig. 32). The initial cost range obtained from the research will provide the manufacturer with a cost limit for producing and pricing their product to be a cost-effective solution for the KSA construction industry.

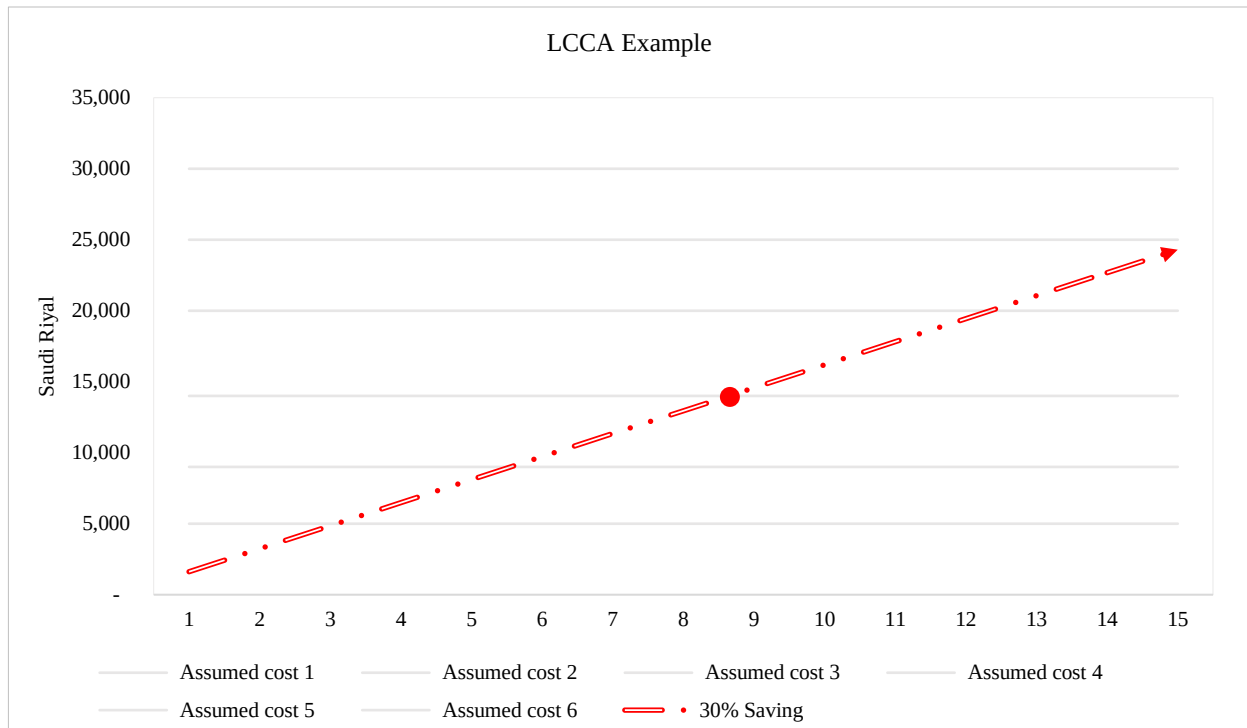


Figure 32. LCCA Illustration Chart 1.

The total energy saving after optimizing the PCM thermal performance is another significant factor in the PCM application decision. The higher the savings the average PCM application provides, the fewer years are needed to pay off the initial cost. Suppose one assumed that the overall energy saving of electricity was about 50%, as the light blue dashed line shows (Fig. 33). In that case, there is a sharper increase and faster intersection of the savings to pay off the initial cost. For example, the assumed initial charge of 15K SAR will be paid off in less than two years. On the other hand, if the total savings of the PCM application resulted in only a 10% overall electricity saving, as the light green dashed line shows (Fig. 33), the annual savings will take 9 years to recoup the lowest initial cost of the PCM application.

Chapter 3 presents an overview of the research methodology and justifies the quantitative approach selection. This chapter explains the research design and quantitative tactics used to investigate the application of PCM in modular housing. The chapter illustrates the proposed tactics of energy simulation, case study selection, comparison metric, and the simulation process. The application of PCM exogenous and endogenous variables are explained in detail according to the study needs. In addition, this chapter explains the importance of conducting an LCCA and provides examples of using the simulation variables in an LCCA to demonstrate the economics of the PCM application.

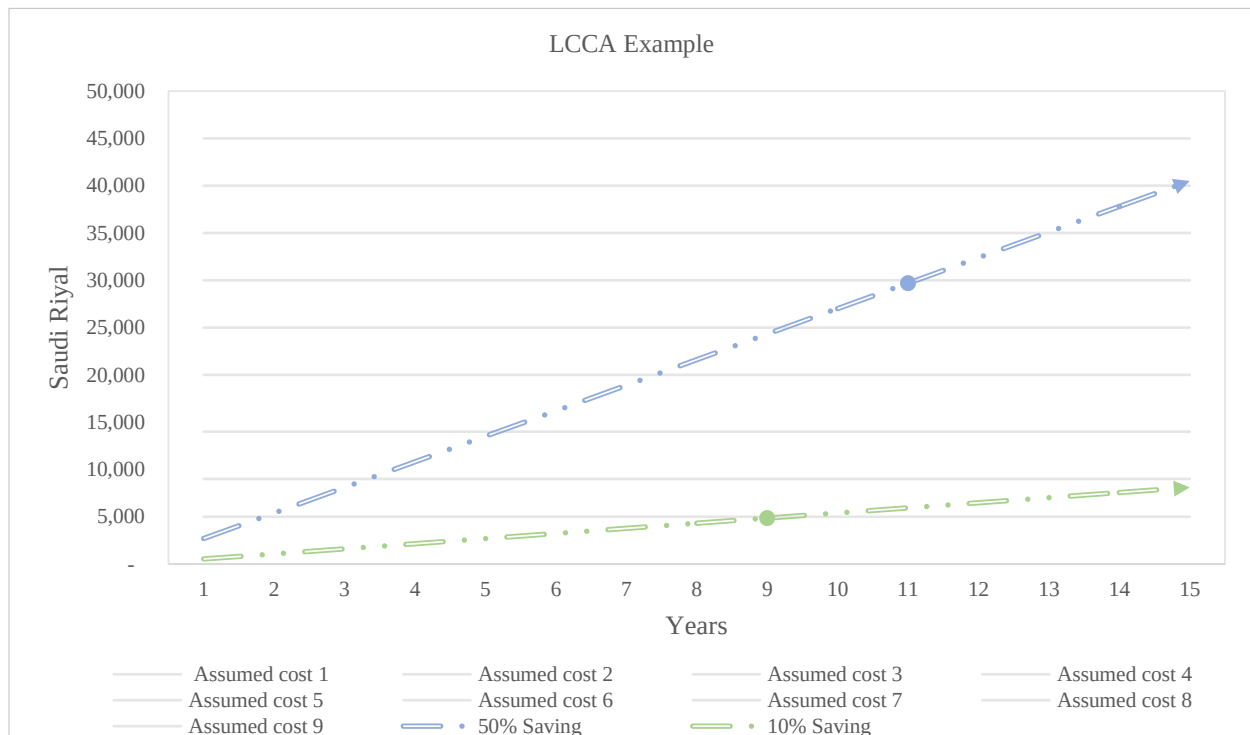


Figure 33. LCCA Illustration Chart 2.

3.11 Cost Modeling Uncertainties Over Time

Cost models can be affected by uncertainties over time, which can impact the model's reliability. The cost model being developed incorporates variables commonly used in cost estimation for construction projects. Uncertainty in cost estimation is common in construction

projects and can be influenced by various factors. In Anita's article "Uncertainty Variables in Cost Estimation for Project Construction" the study has identified 29 uncertain variables in construction project's cost estimation. Related to that, in the present study, we have found that the inflation rate, price fluctuation, and labor costs considerably impact cost estimation.

First, the inflation rate: The cost model is based on three primary variables; including the performance data collected from energy modeling, the price of PCM, and the industry pricing for SIPs. The data from the energy model is a fixed variable in our cost model, while the cost estimation of PCM and SIPs is identified as uncertainties in the model since the pricing is determined by the manufacturers or suppliers. These manufacturers or supplier's pricing rates are influenced by the inflation rate, which can increase the cost of material supply and production. Ultimately leading to an increase in the pricing of PCM and SIPs. Second, PCM development and market changes; The application of PCM is on the rise, and material advancements and developments are showing an increase in its performance, which may lead to an increase in demand and price. Third, labor rates for PCM application and SIPs installation.

A scenario planning approach must be incorporated into the cost model to address these uncertainties. This involves creating multiple scenarios with varying assumptions for inflation rates, assumed percentage increases in PCM prices, and electrical rates to account for different possible outcomes.

The model is designed to estimate the cost of building enclosures using PCM in SIPs, and we have identified the uncertain contributing variables. While the cost model structure is currently applicable to similar projects, it is essential to update the contributing data and information over time to ensure accuracy, especially when applied to different project types or over time when applying the model to other projects.

3.12 Methodology Adaptation Highlight

The applied methodology provides a systematic framework for evaluating contributing variables in specific PCM applications in modular housing. Through the application and integration of parametric analysis and developing an LCCA, the optimal configurations provides balanced energy efficiency and cost-effectiveness. This adaptable approach supports data-driven decision-making in sustainable design and construction which can be applied to various contexts to ensure alignment with both performance and cost-effectiveness goals. It must be noted, however, that the utilized parameters input are unique to the research needs as provided in section 3.12.1. The parameters input can be varied based on the type of project function and goals, which contain varied parameters to test different variables and aim for different outcomes.

3.12.1 Simulation Parameters

The simulation parameters and inputs used to develop the study's base case in the E+ simulation will be itemized in this section. These parameter inputs are specific to the study's goal to investigate the application of PCM in modular housing in Riyadh City, KSA. The study will provide screenshots in the subsequent chapter when developing the base case and adjusting the model while investigating the PCM application. The following section will illustrate the parameters and inputs used in Table 5.

Table 5. Simulation Parameters Inputs.

<u>1/Simulation Parameters:</u>
○ IDF Version: Version aligned with the E+ version used. ○ Simulation Control: 1. Run the simulation for sizing periods" (activated). 2. Run the simulation for weather file run periods" (activated).
1.1 Building Location and Surroundings:
○ Location: Riyadh, Saudi Arabia. ○ Orientation: North (angle set to 0). ○ Terrain: Flat, open countryside.
1.2 Shadow Calculation:
○ Shadow calculation option: Polygon clipping.
1.3 Surface Convection Algorithms:
1. Inside: TARP. 2. Outside: DOE-2.
1.4 Heat Balance Algorithm:
1. CondFD (Conduction Finite Difference).
1.5 Timestep:
1. 60 intervals/hour (1-minute intervals).
<u>2/Location and Climate:</u>
2.1 Location Details:
○ Latitude: 24.774265. ○ Longitude: 46.738586. ○ Elevation: 600 meters (1,950 feet). ○ Time Zone: GMT+3.
2.2 Simulation Run Period:
○ January 1, 2024 – December 31, 2024.
2.3 Ground Temperature:
○ Monthly average values were obtained using Climate Consultant software.
<u>3/ Schedules:</u>
3.1 Schedule Types:
○ Annual occupancy and system schedules. ○ Default options for non-working hours.
<u>4/Surface Construction Elements:</u>
1. Material Properties: ○ OBS, 6-inch concrete slab, roof deck, XPS foam. 2. Building Openings: ○ Windows and glass door thermal properties. 3. PCM Properties: ○ TEMPLOK specifications for PCM.
<u>5/Material Layering Order:</u>
○ Assigned per construction elements.

Table 6. Simulation Parameters Inputs(Continue.

<u>6/Thermal Zones and Surfaces:</u>	
1.	Global Geometry Rule:
	○ Coordinates and zone relationships.
2.	Thermal Zone Configurations:
	○ Three zones specified (e.g., conditioned/unconditioned).
3.	Surfaces and Exposure:
	○ Interior/exterior walls, floors, and roofs.
4.	Fenestration Details:
	○ Windows and doors are assigned to zones.
<u>7/Internal Gains:</u>	
1.	Occupancy: Heat gain linked to activity schedules.
2.	Lighting System: Wattage assigned per zone.
3.	Electrical Equipment: Assigned appliances and equipment.
4.	Water Heater: 40-gallon capacity for three zones.
<u>8/Zone HVAC Control and Thermostats:</u>	
1.	Zone Temperature Control: Thermostats for each zone.
2.	Setpoint Type: Dual setpoints (heating and cooling).
<u>9/Zone HVAC Forced Air Units:</u>	
1.	HVAC Type: Split units with:
	○ Zone controls.
	○ Zone equipment configuration.
	○ Ideal Load Air System option.
2.	Supply Air Temperature: 13°C.
3.	Flow Rate: Configured for peak loads.
<u>10/Output Reporting:</u>	
1.	Report Types:
	○ Hourly, daily, monthly, and annual reports.
2.	Metrics Monitored: Seven criteria (see Chapter 3, Table 4).

3.13 Developed Methodology Overview

The methodology was developed by identifying PCM variables and distinguishing between external and internal factors that affect PCM performance. Next, the study focuses on developing and applying quantitative tactics. The tactics include energy simulation, case studies, defining the energy modeling scope and boundaries, PCM selection, simulation context, and the application of

PCM in several scenarios. With defined criteria and metrics that prioritize energy efficiency and cost-effectiveness, optimization is a key focus. Furthermore, the methodology developed an LCCA model to evaluate the economic feasibility of PCM obtained variables under varying conditions, including uncertainties over time.

Chapter 4: E+ Simulation

The research methodology involves using energy simulation as the primary approach in the study. This includes conducting energy simulations on 13 different models in E+ to optimize the thickness and location of the PCM by varying both location within the wall assembly and thickness (Fig 22). The simulation results were compared to an established base case with no PCM Model (A) to determine the optimal model with PCM. Chapter four provides a detailed description of the development of the research base case in E+. It also illustrates and explains the process involved in creating all the research models and their respective variants. The simulation series results were analyzed and discussed in the following chapter to demonstrate the determination of the optimum model selection.

The coming section aims to demonstrate how to build a model in E+ and provides readers with knowledge about the parameters used in E+ and their role in the model simulation. Therefore, in this section, the researcher will develop the research base case model (A) to be used throughout the entire study and will show the process needed to build the model. The section will also provide details about parameter options in E+ selection, along with screenshots and a narrative description of the parameters selected.

4.1 Research Base Case Modeling

E+ interface's window displays the simulation file selection, weather file selection, simulation run button, the Input Data Files (IDF) editor, and simulation results report to the users (Fig. 34). The IDF lists the data inputs to build the simulation model properties and specifications that were used in the simulation. The IDF is designed to provide users with the ability to create or edit input data files. However, the IDF Editor does not check the input's validity. Instead, it offers

default numeric values for user assistance, and any input values higher than the normal range will be highlighted.

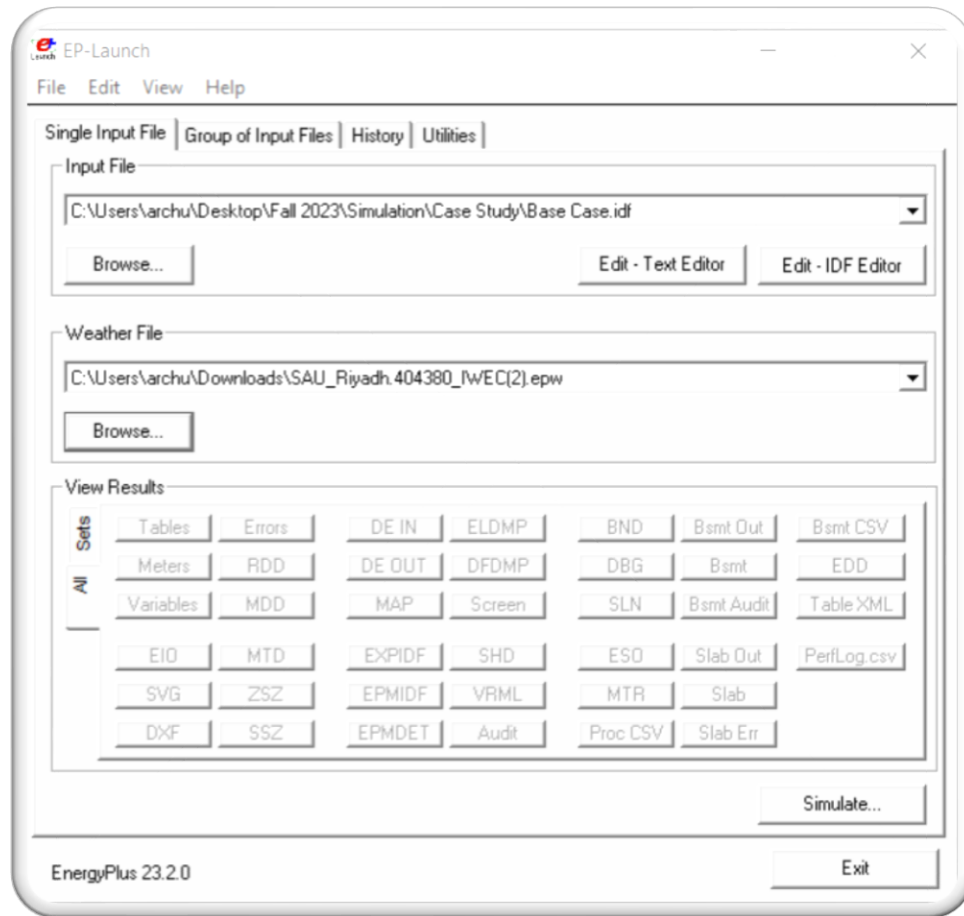


Figure 34. E+ Interface (E+).

Opening the IDF editor allows users to input general information about the model, properties, and data specifications (Fig. 35). A class list related to the model specifications will appear, presenting a list of options for data input and selection. As the software provides various options for simulation inputs, the study will highlight the class list used in Group 1 options, in addition to those selected from the dropped options within Group 1 options. The following sections will illustrate the IDF's class list, the selected options, and the added values as the study develops the base case model.

4.1.1 Simulation Parameters

The first input of the class list is the simulation parameters, the first parameter input is the IDF version utilized in the simulation (Fig. 35). The goal of this input is to align the IDF version with the E+ version to prevent errors. IDF files are not compatible with newer E+ versions and users can update their IDF using the version updater document to make them compatible with newer versions. The study utilized the latest E+ version to generate the base case IDF, ensuring consistency throughout the research.

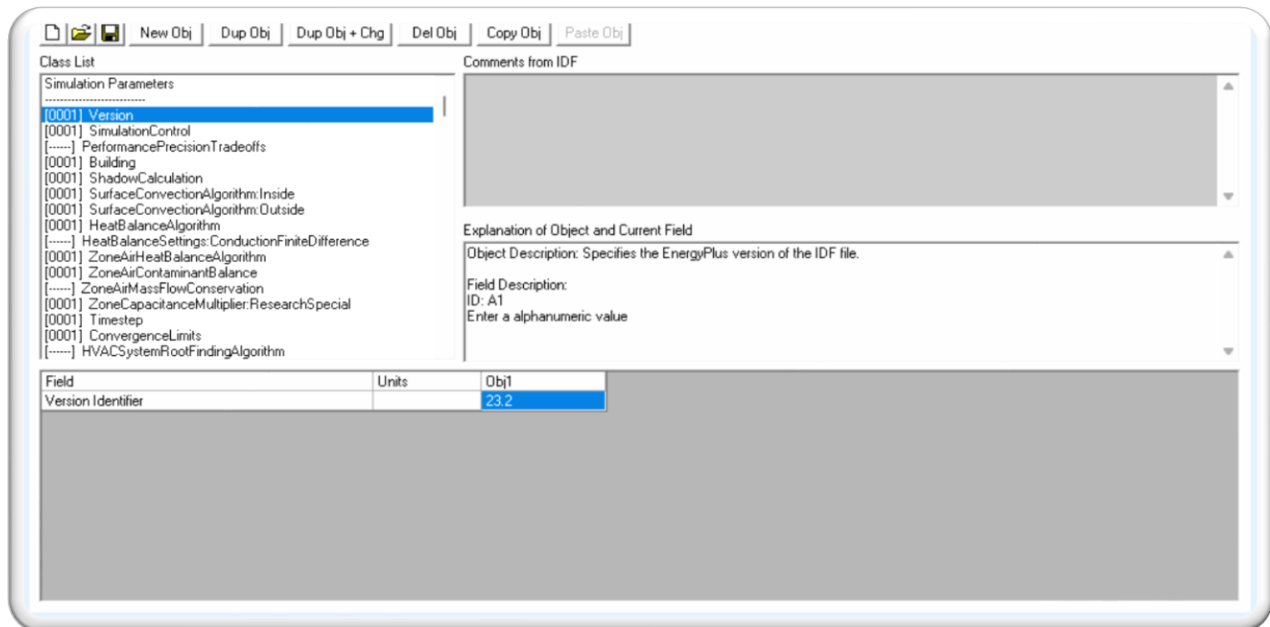


Figure 35. IDF Class List (E+).

The second parameter in the simulation control used is the simulation control input which provides the user the option to choose the specific calculations for E+ simulation (Fig. 36). Users can customize the simulation to include or exclude sizing calculations and annual weather file simulations. Sizing runs are typically fast and don't significantly impact the overall simulation time. The simulation control input offers six yes/no options for various combinations of simulation runs. In our case, the study intends to use the calculation for designed days and periods simulation

to monitor the HVAC system loads and envelop performance under the impact of PCM utilization. Therefore, the only two options that will be activated in this group are the “run simulation for sizing periods” option and the “run simulation for weather file run periods” option and the rest within the parameter will be set to default setup. The selection of these two options will give the ability for the following calculation options E+ uses.

Option one is the design day simulation which is commonly employed for load calculations and equipment sizing. It involves creating a full day of weather data (e.g., air temperatures, solar radiation) using specified values. Default range multipliers are typically used, but users can customize their multiplier schedule. One "humidity indicating condition" is chosen for calculating the constant humidity ratio throughout the day, but this can be altered with a relative humidity schedule or by generating an hourly wet-bulb temperature profile. Multiple design days can be defined.

Option two is the weather file days option which allows one to choose a specific period from the attached weather file for load calculations or equipment sizing. The selected period can range from a single day, weeks, or a longer duration. However, for sizing calculations, it's advisable to also consider using design days that represent more long-term extremes or conditions. The two options represent the aim of the study since the research design plans to monitor the performance of the base case and the series of the other 12 models for the year's four seasons. In this parameter, the needed options that will fit the research plan are activated while the non-necessary parameters are excluded (Fig. 36).

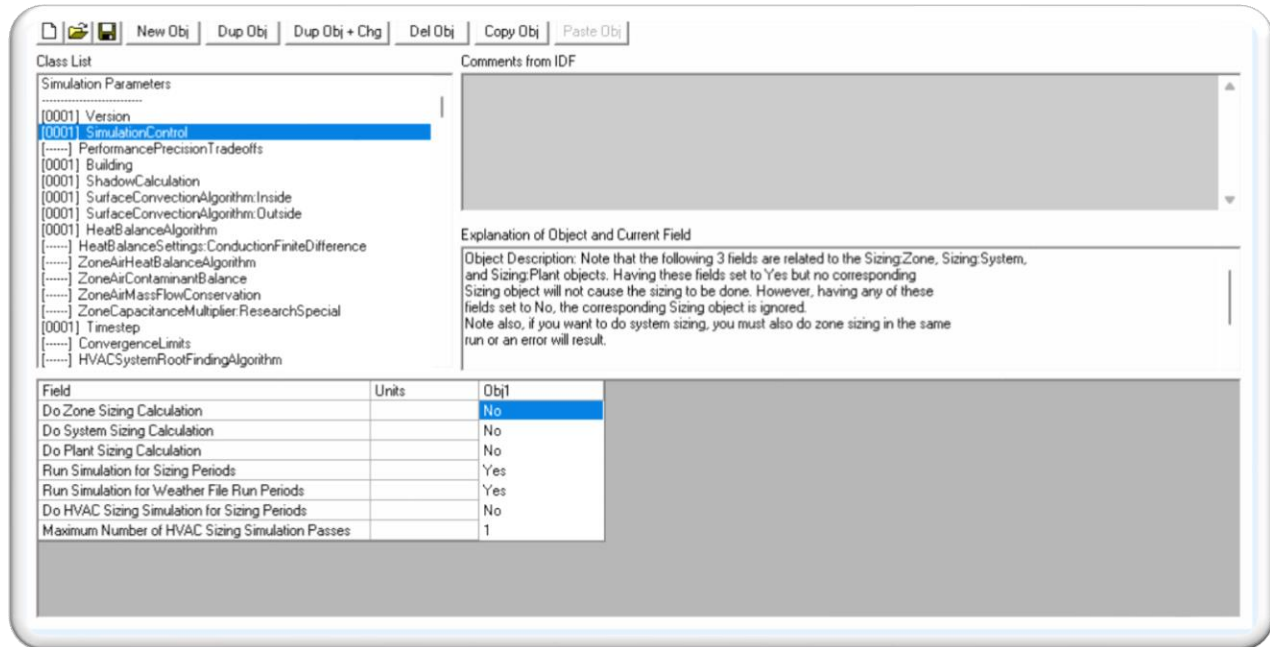


Figure 36. Simulation Control Selection (E+).

The third parameter describes the building's location and surroundings. It has correlations with the parameter inputs that will come in other sections named "weather station" and "height variation" especially in the "terrain" field (Fig. 37). In the study's base case, the location was chosen to be in the countryside with no nearby buildings or shadows to expose the model to the highest temperatures without shading and with highest exposure to environmental impact. The required inputs for these parameters are to specify the building orientation and terrain. The building entrance is oriented toward true north, thus the angle in the input is set to zero. The terrain is specified in the software options to match the case study location as a "country" option, defined as flat and open country. The solar radiation inputs are set to minimize shading, while other inputs are left at their default settings (Fig. 37).

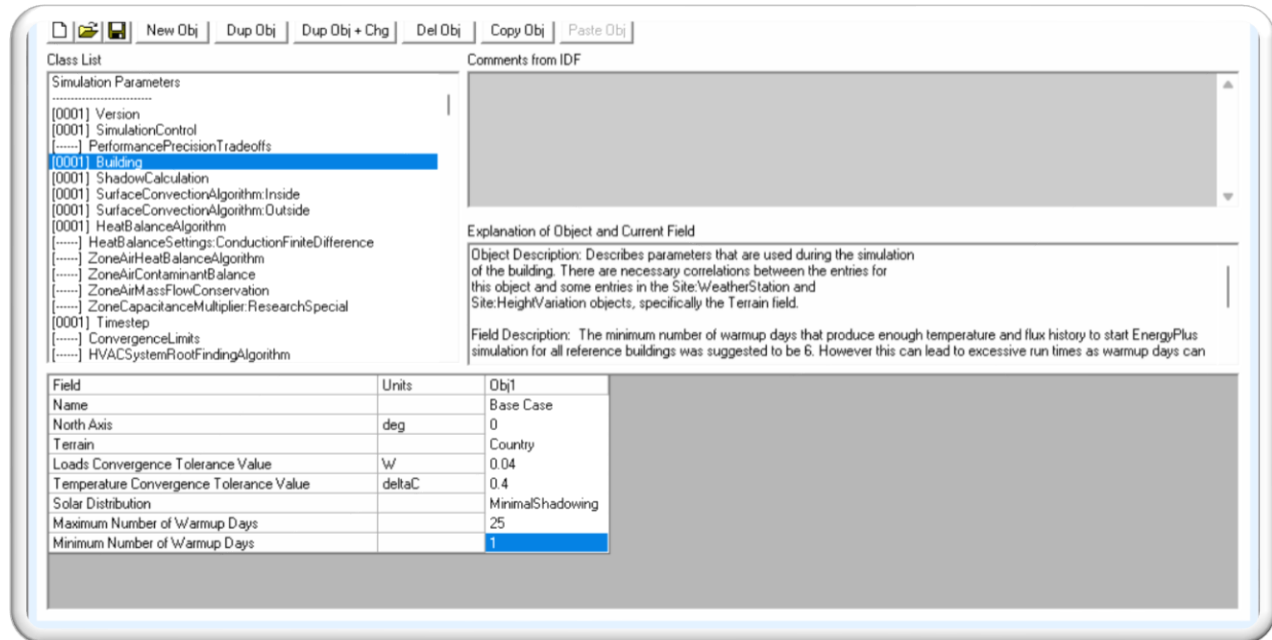
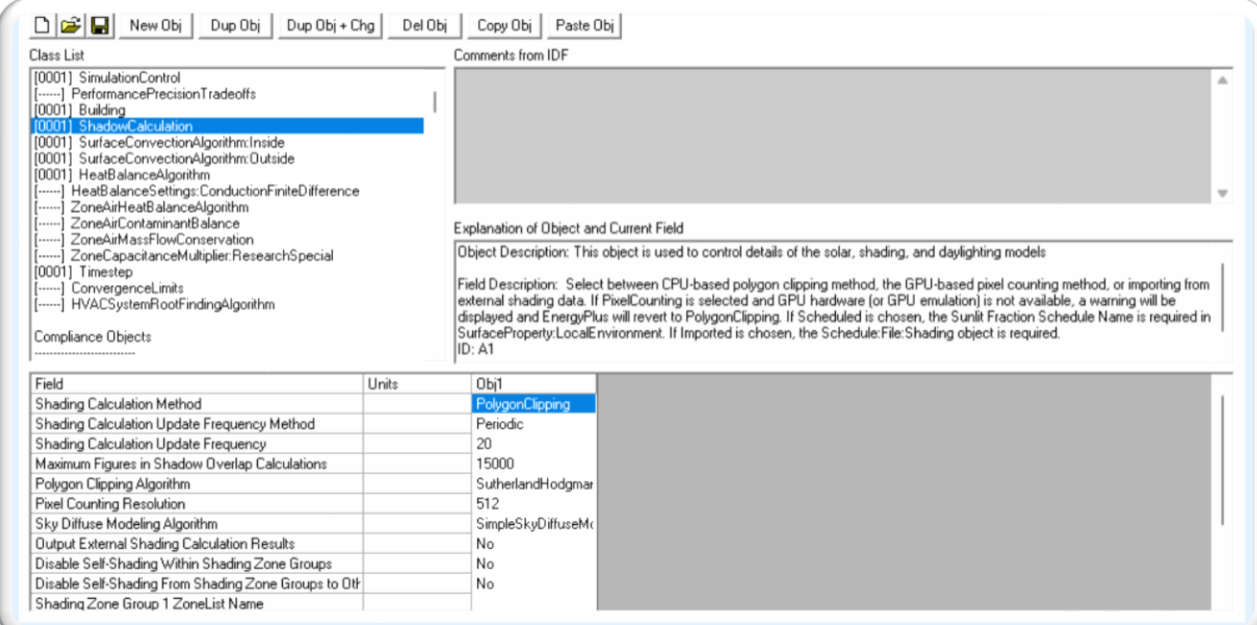


Figure 37. Building Parameters Inputs (E+).

The rest of the simulation parameters needed to develop the base case in the study of shadow calculation, surface convection algorithm inside, and surface convection algorithm outside were set to default options in the IDF, except for the heat balance algorithm and time step parameters. The shadow calculation was set to the 'shadow calculation, polygon clipping' option (Fig. 38).

The surface convection algorithm inside used the default option 'TARP' (Fig. 39). TARP is a natural convection model driven directly by the Walton algorithm (1983). The surface convection algorithm outside selection was set to the DOE-2 option (Fig. 40), which is a convection model resulting from a combination of the MoWiTT and BLAST models (LBL 1994). The heat balance algorithm parameter was set to the 'CondFD' algorithm, and the rest of the 'Category' options were set to default (Fig. 41). The study needs an advanced method to calculate the heat balance to calculate PCM application which would be fulfilled easily by using the CondFD algorithm as explained in the research methodology in chapter 3 in E+ algorithm section.

The timestep parameter specifies the time interval for the simulation, also referred to as the Zone Timestep. It's a crucial input for calculating heat transfer and loads in the Zone Heat Balance Model. Users enter a value that represents the number of time intervals within an hour. The allowed values range from 1 to 60. For the aim of accurate results, the study selected 60 which is the maximum value. The calculations will be every minute to monitor the changes in temperatures and their impact on the heat transferred to the zones per minute (Fig. 42).



Class List

- [0001] SimulationControl
 - [.....] PerformancePrecisionTradeoffs
- [0001] Building
 - [0001] ShadowCalculation
 - [0001] SurfaceConvectionAlgorithm:Inside
 - [0001] SurfaceConvectionAlgorithm:Outside
 - [0001] HeatBalanceAlgorithm
 - [.....] HeatBalanceSettings:ConductionFiniteDifference
 - [.....] ZoneAirHeatBalanceAlgorithm
 - [.....] ZoneAirContaminantBalance
 - [.....] ZoneAirMassFlowConservation
 - [.....] ZoneCapacitanceMultiplier:ResearchSpecial
 - [0001] Timestep
 - [.....] ConvergenceLimits
 - [.....] HVACSystemRootFindingAlgorithm

Compliance Objects

Comments from IDF

Explanation of Object and Current Field

Object Description: This object is used to control details of the solar, shading, and daylighting models

Field Description: Select between CPU-based polygon clipping method, the GPU-based pixel counting method, or importing from external shading data. If PixelCounting is selected and GPU hardware (or GPU emulation) is not available, a warning will be displayed and EnergyPlus will revert to PolygonClipping. If Scheduled is chosen, the Sunlit Fraction Schedule Name is required in SurfaceProperty:LocalEnvironment. If Imported is chosen, the Schedule:File:Shading object is required.
ID: A1

Field	Units	Obj1
Shading Calculation Method		PolygonClipping
Shading Calculation Update Frequency Method		Periodic
Shading Calculation Update Frequency		20
Maximum Figures in Shadow Overlap Calculations		15000
Polygon Clipping Algorithm		SutherlandHodgmar
Pixel Counting Resolution		512
Sky Diffuse Modeling Algorithm		SimpleSkyDiffuseM
Output External Shading Calculation Results		No
Disable Self-Shading Within Shading Zone Groups		No
Disable Self-Shading From Shading Zone Groups to Oth		No
Shading Zone Group 1 ZoneList Name		

Figure 38. Shadow Calculations Inputs (E+).

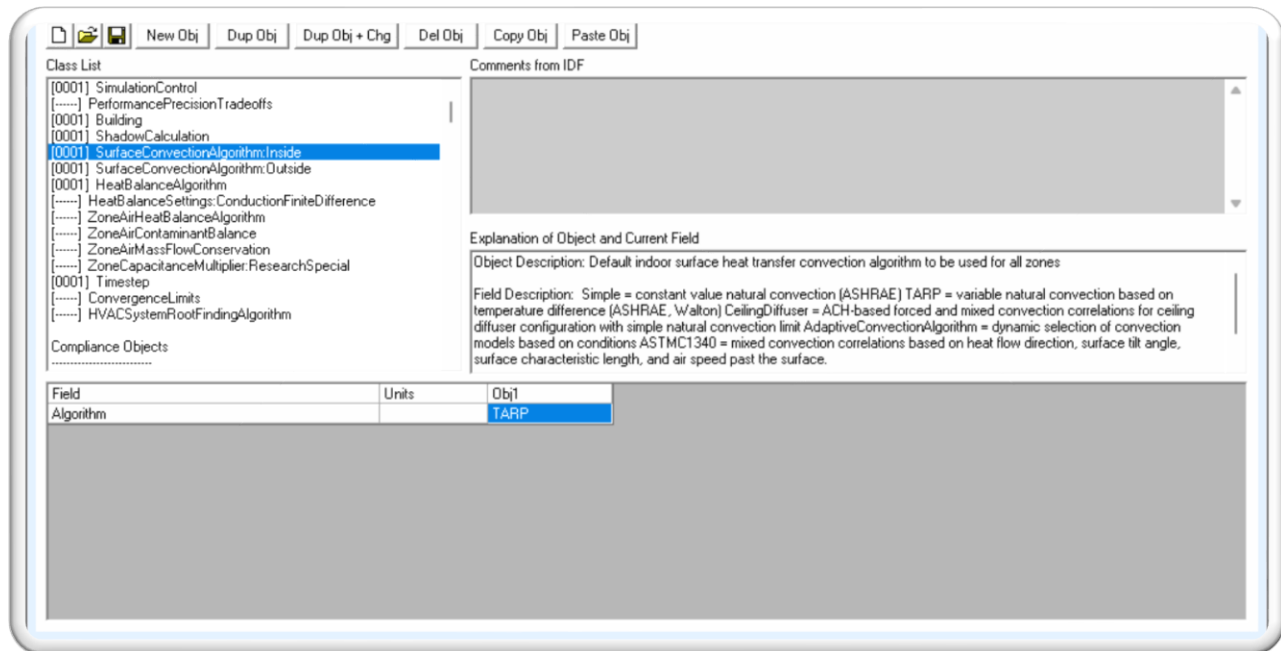


Figure 39. Surface Convection Algorithm Inside Selection (E+).

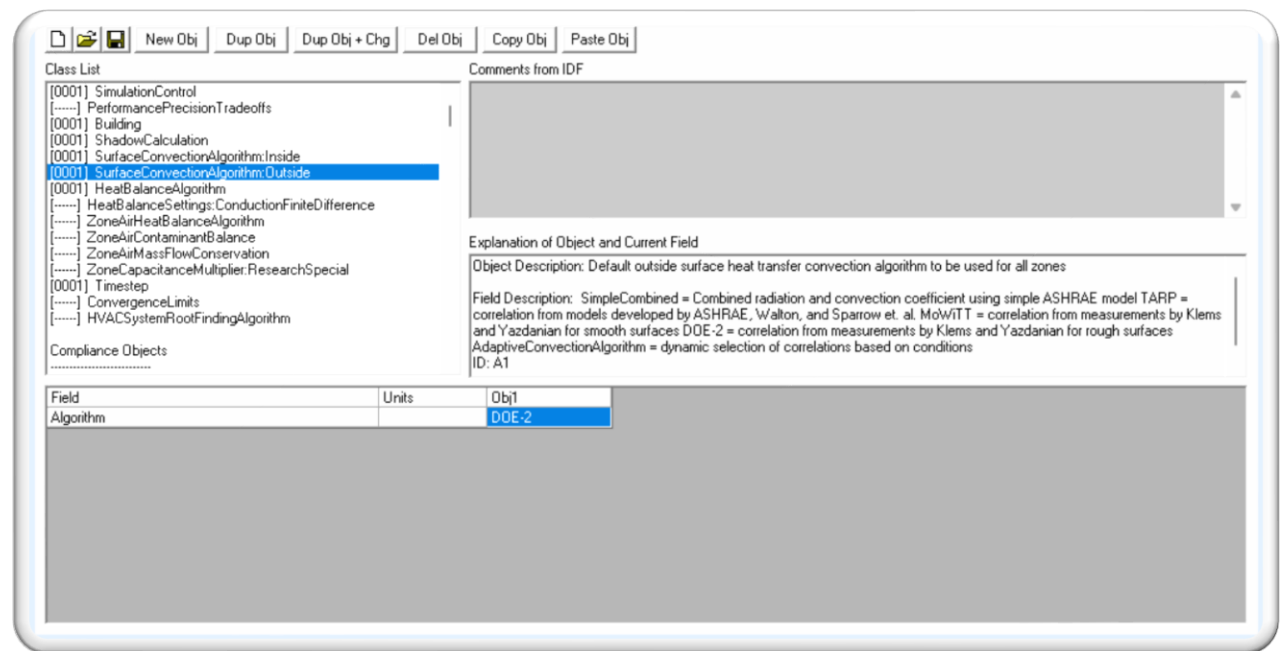


Figure 40. Surface Convection Algorithm Outside Selection (E+).

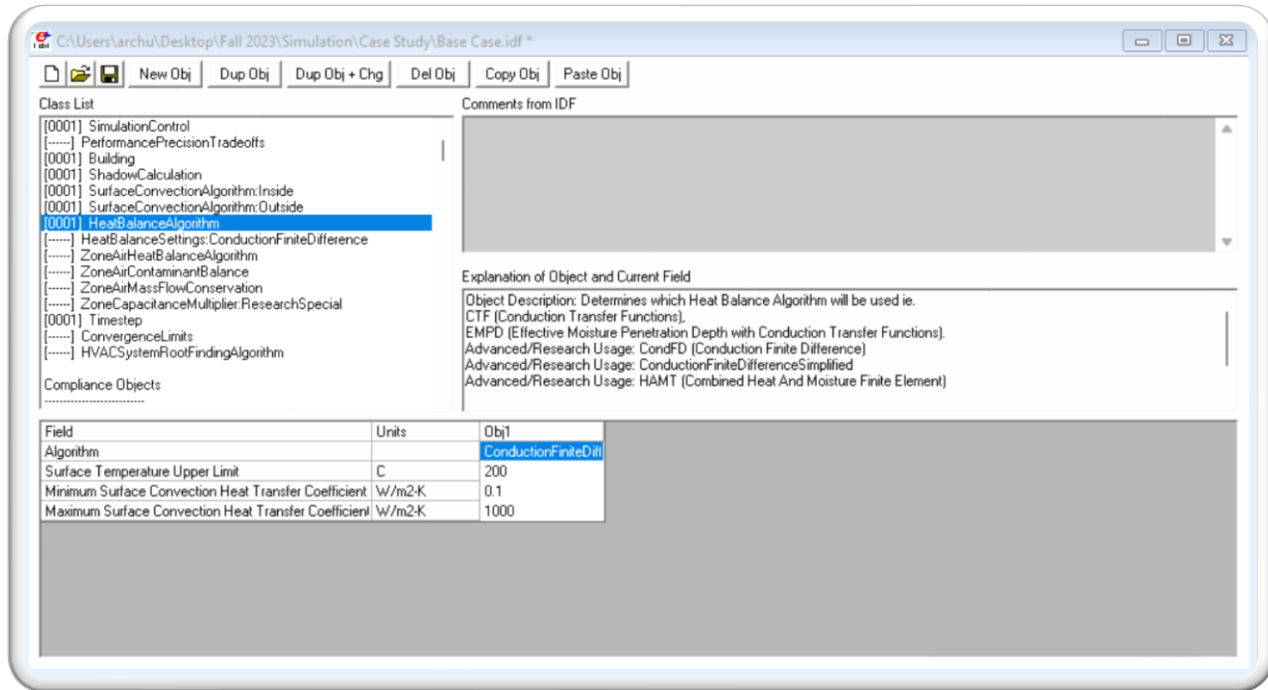


Figure 41. Heat Balance Algorithm Selection (E+).

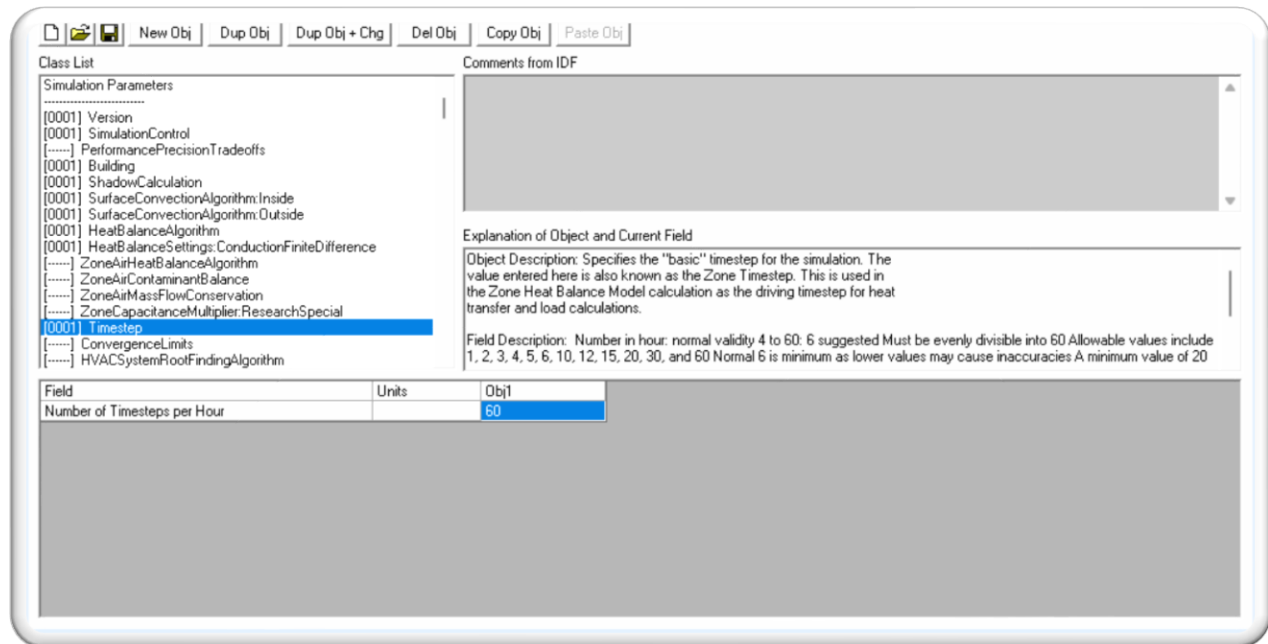
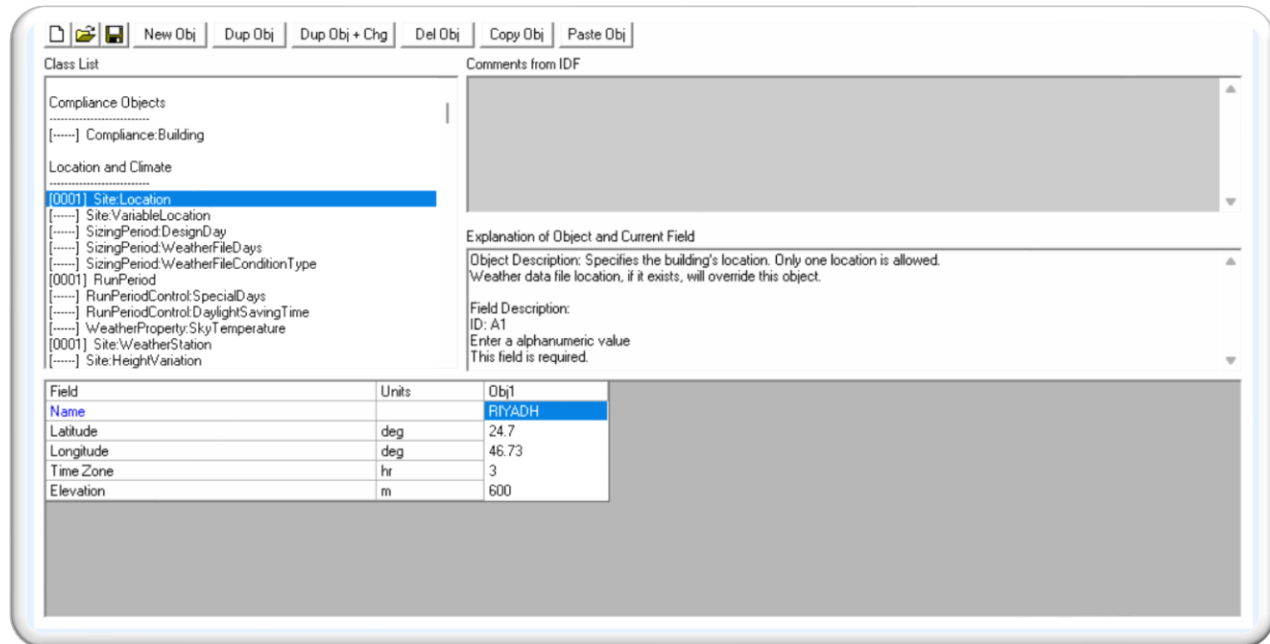


Figure 42. Timestep Selected Value (E+).

4.1.2 Location and Climate

The first required input in this category is the base case location. The location is specified to be in Riyadh, the capital of KSA. Additionally, the latitude and longitude degrees for the location have to be entered. Riyadh, Saudi Arabia has a latitude of 24.774265 and a longitude of 46.738586. The location's elevation above sea level and time zone are also required. Riyadh is located approximately 1,950 feet (600 meters) above sea level and its time zone is (GMT+3). These values were input into the location category as shown in (Fig. 43).



Field	Units	Obj1
Name		RIYADH
Latitude	deg	24.7
Longitude	deg	46.73
Time Zone	hr	3
Elevation	m	600

Figure 43. Location Inputs (E+).

The second required input in the category is the simulation run period. It allows the user to specify their preferred simulation time frame. As demonstrated in Chapter Three, this study aims to simulate a real-life model through the application of simulation. Therefore, the input for the

simulation run in this category is set to begin on Monday, January 1st, 2024, and end on Wednesday, December 31st, 2024 to gather data for the year's four seasons (Fig. 44).

The screenshot shows the EnergyPlus (E+) software interface. The 'Class List' on the left has 'RunPeriod' selected. The 'Field' table at the bottom lists parameters for the 'Run Period' object. The 'Units' and 'Obj' columns show values like 1, 2024, and Monday.

Field	Units	Obj
Name		Run Period
Begin Month		1
Begin Day of Month		1
Begin Year		2024
End Month		12
End Day of Month		31
End Year		2024
Day of Week for Start Day		Monday
Use Weather File Holidays and Special Days		No
Use Weather File Daylight Saving Period		No
Apply Weekend Holiday Rule		No

Figure 44. Simulation Run period Inputs (E+).

The third input in this category is the ground temperature beneath the building. The values required represent the ground temperature for the entire year, broken down by month. For this, the research utilized the Climate Consultant app to obtain the average temperature data for the base case location by aggregating information from Riyadh city's weather file (Fig. 45). The acquired data were input into the ground temperature category, as shown in (Fig. 46).

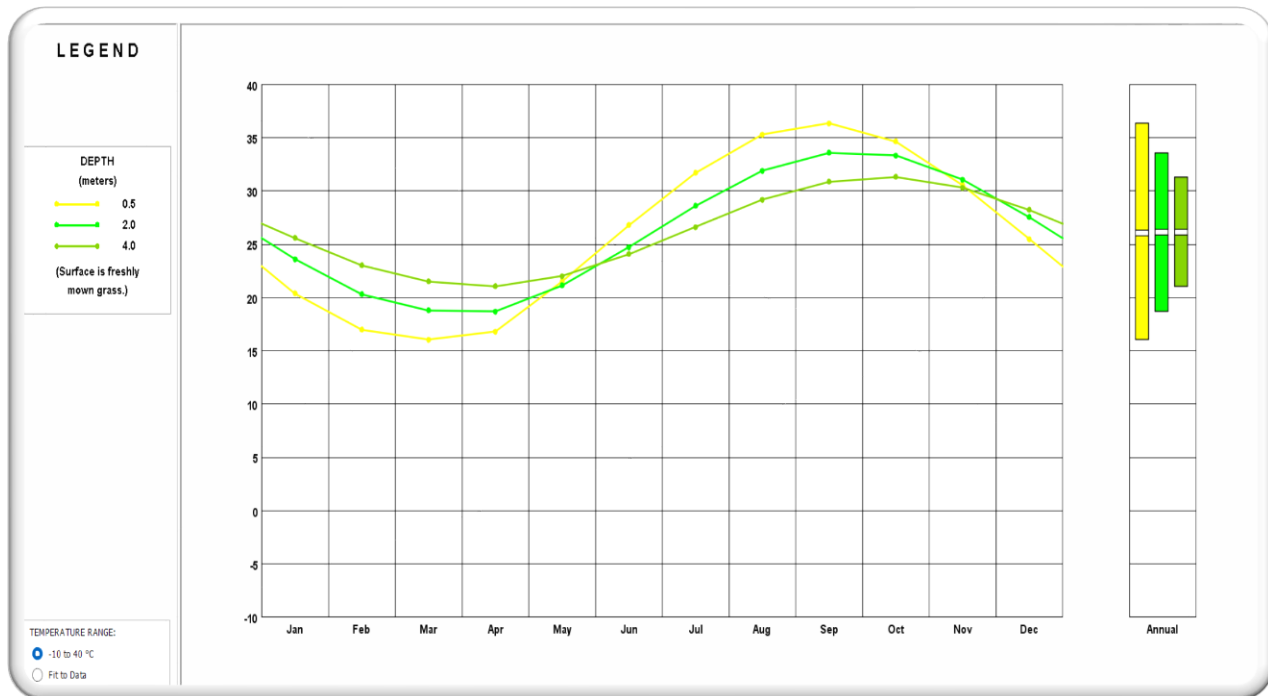


Figure 45. Riyadh Ground Temperature Monthly Average (Climate Consultant).

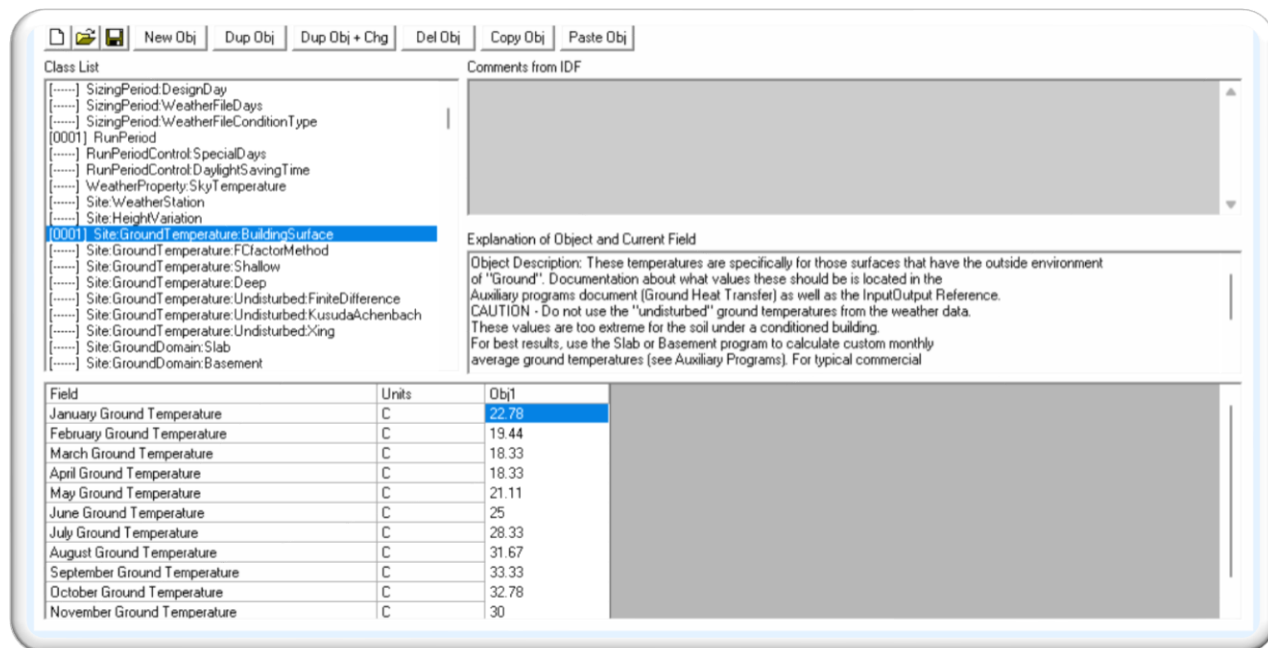


Figure 46. Ground Temperature Inputs (E+).

4.1.3 Schedules

E+ provides a variety of types of schedules allowing users to create custom schedules that align with specific building and system behaviors in their simulations. This parameter defined occupancy hours for the building that in turn affect the operation hours of the lighting system, HVAC system, equipment usage, and temperature setpoints. The software offers three types of schedules selected by the user: daily, weekly, and yearly. In addition, it allows customized schedules that can exclude specific days and holidays that are particularly valuable for larger projects. The selected option in this category is the annual option with all working hours for occupancy and system assigned, while the other option that impacts the simulation is set to the default. The input values are assigned for an entire year to align with each zone's utilization during working hours, excluding non-working hours during the day (Fig. 47).

The screenshot shows the E+ software interface with the 'Schedules' class list on the left. The 'Cooling New' object is selected, and its configuration is shown in the 'Obj1' column of the table below. The 'Obj2' column shows the 'Heating New' object configuration. The table has columns for Field, Units, Obj1, and Obj2.

Field	Units	Obj1	Obj2
Name		Cooling New	Heating New
Schedule Type Limits Name		Temperature1	Temperature1
Field 1	varies	Through: 12/31	Through: 12/31
Field 2	varies	For: All days	For: All days
Field 3	varies	Until: 24:00	Until: 24:00
Field 4	varies	24	18
Field 5	varies		
Field 6	varies		
Field 7	varies		
Field 8	varies		
Field 9	varies		

Figure 47. Base Case Schedule Inputs (E+).

4.1.4 Surface Construction Elements

E+ requires data about all the surfaces and construction used in the building to create the model envelope. It describes the physical properties of the building envelope and interior elements, such as walls, roofs, floors, windows, and doors. The simulation included the following four inputs about the study's base case. The first input is to identify the materials used in the building construction. All the materials used have to be identified, and inputs about their properties and specifications have to be added. The inputs added to the case study are the OBS, concrete slab 6in, roof deck, and XPS foam (Fig. 48).

Class List

- [0009] Schedule:Day:Interval
- [.....] Schedule:Day:List
- [0017] Schedule:Week:Daily
- [.....] Schedule:Week:Compact
- [0017] Schedule:Year
- [0008] Schedule:Compact
- [0007] Schedule:Constant
- [.....] Schedule:File:Shading
- [.....] Schedule:File

Surface Construction Elements

- [0005] Material
- [.....] Material:NoMass
- [.....] Material:InfraredTransparent
- [.....] Material:AirGap
- [.....] Material:RoofVegetation
- [.....] WindowMaterial:SimpleGlazingSystem

Comments from IDF

Explanation of Object and Current Field

Object Description: Regular materials described with full set of thermal properties

Field Description:

ID: N2

No default value available

Range: 0 < X but no maximum

This field is required.

Field	Units	Obj1	Obj2	Obj3	Obj4	Obj5
Name		25C PCM	Concrete Slab 6in	OSB	Roof Deck	XPS Foam
Roughness		VeryRough	MediumRough	Smooth	Smooth	MediumRough
Thickness	m	0.005	0.15	0.019	0.019	0.15
Conductivity	W/m-K	1.1445	1.75	0.163	0.163	0.032
Density	kg/m3	1525	2240	600	600	32
Specific Heat	J/kg-K	3140	837	1210	1210	1400
Thermal Absorptance		0.9	0.9	0.9	0.9	0.9
Solar Absorptance		0.7	0.85	0.7	0.6	0.7
Visible Absorptance		0.7	0.85	0.7	0.67	0.7

Figure 48. Building Materials Input (E+).

The second input is the building opening windows and glass doors in the base case. The specifications about the type of glass and thermal properties were added to the model in this section (Fig. 49). The third input in this section is the phase change hysteresis properties, which are added to the model through a different section from the other materials for its different properties. The properties of PCM that were utilized in the study have to be added as inputs in this section to be

utilized later in the other model's simulation. The technical specifications of TEMPLOK were added in this input section (Fig. 50). The fourth input is about the building construction, which required the material layering order for the building elements as shown in (Fig. 51).

Field	Units	Obj1
Name		CLEAR 3MM
Optical Data Type		SpectralAverage
Window Glass Spectral Data Set Name		
Thickness	m	0.003
Solar Transmittance at Normal Incidence		0.837
Front Side Solar Reflectance at Normal Incidence		0.075
Back Side Solar Reflectance at Normal Incidence		0.075
Visible Transmittance at Normal Incidence		0.898
Front Side Visible Reflectance at Normal Incidence		0.081
Back Side Visible Reflectance at Normal Incidence		0.081
Infrared Transmittance at Normal Incidence		0

Figure 49. Glazing Inputs (E+).

Field	Units	Obj1	Obj2	Obj3	Obj4	Obj5
Name		25C PCM	Concrete Slab 6in	OSB	Roof Deck	XPS Foam
Roughness		VeryRough	MediumRough	Smooth	Smooth	MediumRough
Thickness	m	0.006	0.15	0.019	0.019	0.2
Conductivity	W/m-K	1.09	1.75	0.163	0.163	0.032
Density	kg/m3	1525	2240	600	600	32
Specific Heat	J/kg-K	3140	837	1210	1210	1400
Thermal Absorptance		0.9	0.9	0.9	0.9	0.9
Solar Absorptance		0.7	0.85	0.7	0.6	0.7
Visible Absorptance		0.7	0.85	0.7	0.67	0.7

Figure 50. PCM TEMPLOK Input (E+).

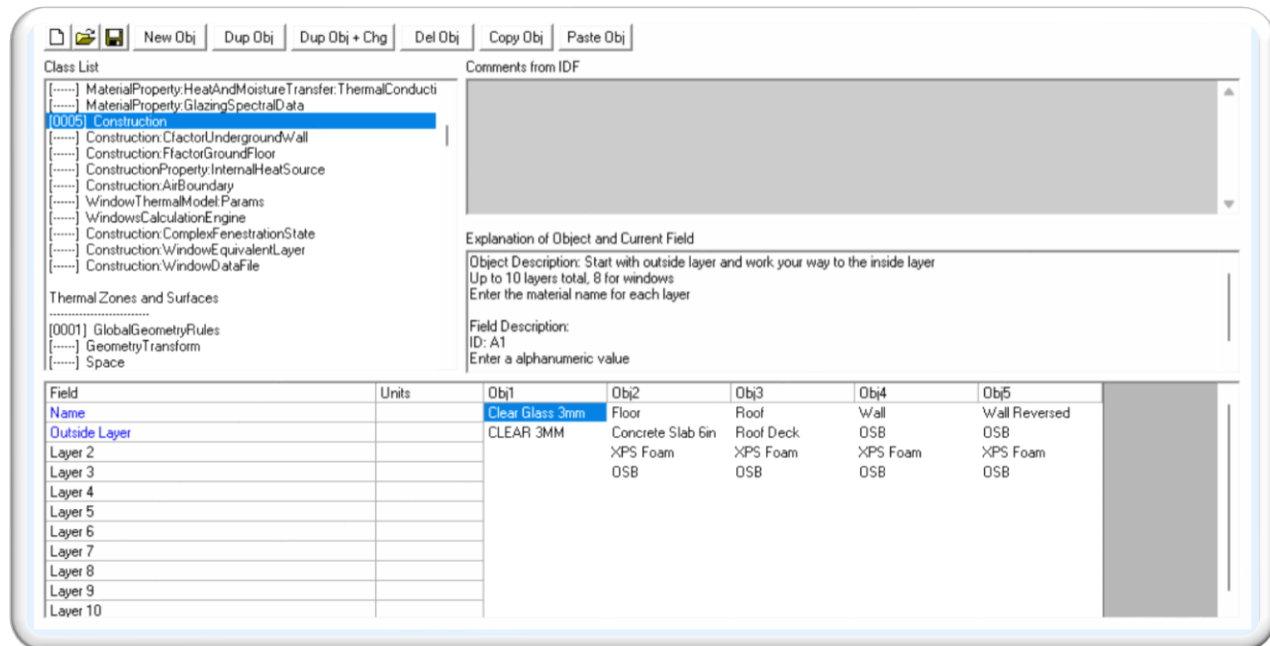


Figure 51. Base Case Construction Inputs (E+).

4.1.5 Thermal Zones and Surfaces

E+ provides the user with the option of creating spaces inside the building known as zones. Zoning is very important to provide different spaces with different characteristics such as conditioned and unconditioned zone in addition to the type of surfaces creating the zone and their exposure to the environment. In this section, E+ is required to input the building angle to organize the zones and their location within the building and global context. In our study, the base case has three different zones as illustrated in Chapter Three all the zones are input by specifying the surrounding surfaces as interior or exterior or their exposure. This first input in the category is the global geometry rule which is about the building coordination and the zones' relation to the degrees input in the previous section (Fig. 52). The second input is about the thermal zones coordination utilized in the building (Fig. 53). The third input in this section is about the zones surfaces, all the 3 zones with their 6 surfaces were added in addition for being a wall, floor, and roof in addition to

their exposure (Fig. 54). The fourth input is the fenestration surface details which is related about the window and door used details and coordination within the base case (Fig. 55).

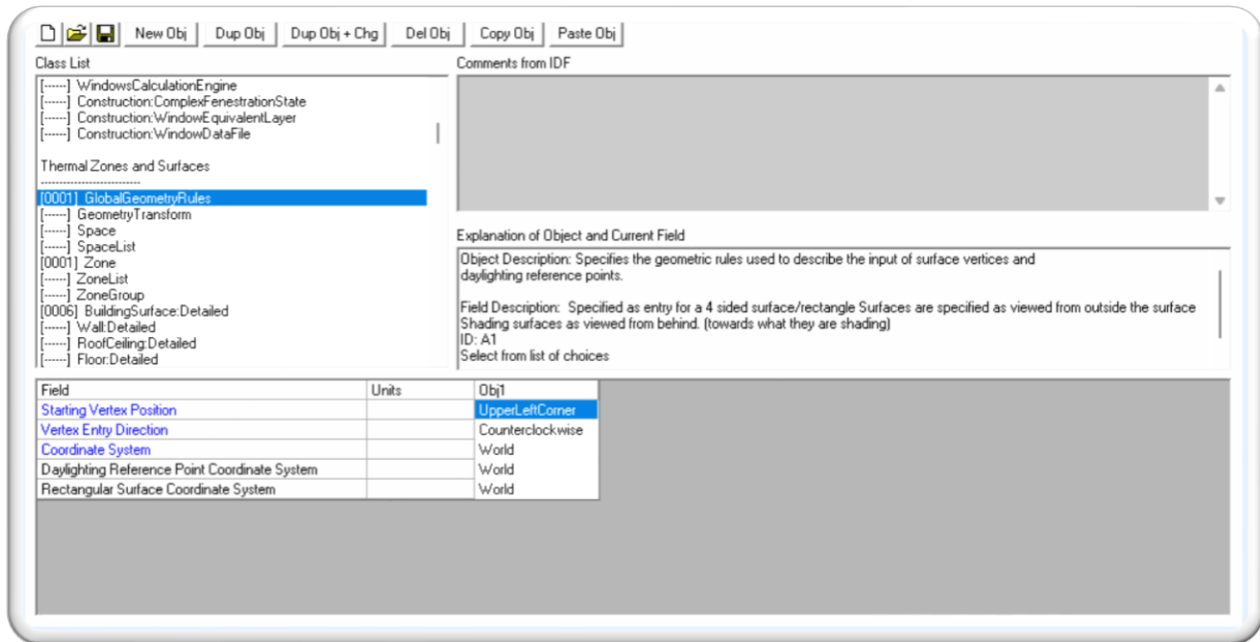


Figure 52. Geometry Inputs (E+).

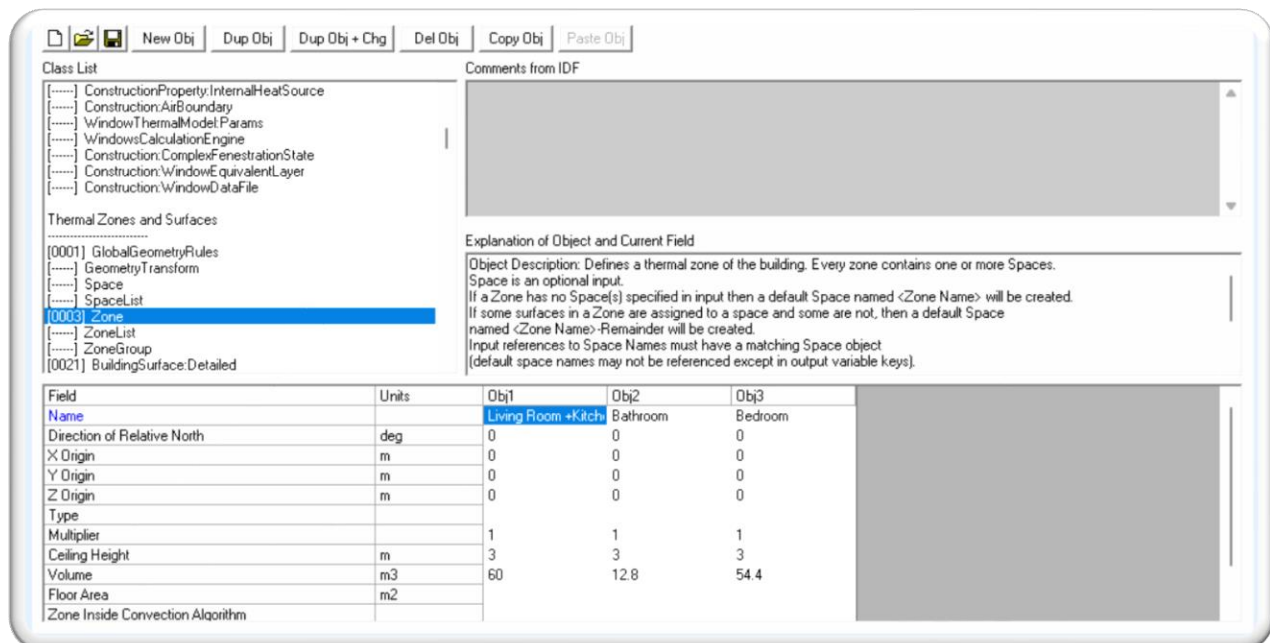


Figure 53. Thermal Zones Coordination Inputs (E+).

Class List: [New Obj] [Dup Obj] [Dup Obj + Chg] [Del Obj] [Copy Obj] [Paste Obj]

- [] Space
- [] SpaceList
- [0003] Zone
- [] ZoneList
- [] ZoneGroup
- [0021] BuildingSurface:Detailed
- [] Wall:Detailed
- [] RoofCeiling:Detailed
- [] Floor:Detailed
- [] Wall:Exterior
- [] Wall:Adiabatic
- [] Wall:Underground
- [] Wall:Interzone
- [] Roof
- [] Ceiling:Adiabatic
- [] Ceiling:Interzone
- [] Floor:GroundContact
- [] Floor:Adiabatic

Comments from IDF

Explanation of Object and Current Field

Object Description: Allows for detailed entry of building heat transfer surfaces. Does not include subsurfaces such as windows or doors.

Field Description: Zone the surface is a part of.
ID: AA
Select from list of objects
This field is required.

Field	Units	Obj1	Obj2	Obj3	Obj4	Obj5	Obj6	Obj7	Obj8	Obj9	Obj10
Name		Face 0	Face 1	Face 2	Face 3	Face 4	Face 5	Face 7	Face 18	Face 19	Face 20
Surface Type		Floor	Roof	Wall	Wall	Wall	Wall	Wall	Floor	Roof	Wall
Construction Name		Floor	Roof	Wall	Wall Reversed	Wall	Wall	Wall	Floor	Roof	Wall Rev
Zone Name		Living Room + Kitch	Living Room + Kitch	Living Room + Kitch	Living Room + Kitch	Living Room + Kitch	Living Room + Kitch	Living Room + Kitch	Bathroom	Bathroom	Bathroom
Space Name											
Outside Boundary Condition		Ground	Outdoors	Surface	Surface	Outdoors	Outdoors	Outdoors	Ground	Outdoors	Surface
Outside Boundary Condition Object				Face 22	Face 14						Face 16
Sun Exposure		NoSun	SunExposed	NoSun	NoSun	SunExposed	SunExposed	SunExposed	NoSun	SunExposed	NoSun
Wind Exposure		NoWind	WindExposed	NoWind	NoWind	WindExposed	WindExposed	WindExposed	NoWind	WindExposed	NoWind
View Factor to Ground											
Number of Vertices											
Vertex 1 X-coordinate	m	-0.8	-4.1	-0.8	-0.8	-0.8	-4.1	-4.1	0.9	-0.8	0.9
Vertex 1 Y-coordinate	m	3.2	3.2	3.2	0.8	-0.4	-0.4	3.2	3.2	3.2	3.2
Vertex 1 Z-coordinate	m	0	4	4	4	4	4	4	0	4	4
Vertex 2 X-coordinate	m	-0.8	-4.1	-0.8	-0.8	-4.1	-4.1	-0.8	0.9	-0.8	0.9
Vertex 2 Y-coordinate	m	0.8	-0.4	0.8	-0.4	-0.4	3.2	3.2	0.8	0.8	0.8
Vertex 2 Z-coordinate	m	0	4	4	4	4	4	4	0	4	4

Figure 54. Base Case Fenestration Inputs (E+).

Class List: [New Obj] [Dup Obj] [Dup Obj + Chg] [Del Obj] [Copy Obj] [Paste Obj]

- [0021] BuildingSurface:Detailed
- [] Wall:Detailed
- [] RoofCeiling:Detailed
- [] Floor:Detailed
- [] Wall:Exterior
- [] Wall:Adiabatic
- [] Wall:Underground
- [] Wall:Interzone
- [] Roof
- [] Ceiling:Adiabatic
- [] Ceiling:Interzone
- [] Floor:GroundContact
- [] Floor:Adiabatic
- [] Floor:Interzone
- [0003] FenestrationSurface:Detailed
- [] Window
- [] Door
- [] GlazedDoor

Comments from IDF

Explanation of Object and Current Field

Object Description: Allows for detailed entry of subsurfaces (windows, doors, glass doors, tubular daylighting devices).

Field Description: ID: A1
Enter an alphanumeric value
This field is required.

Field	Units	Obj1	Obj2	Obj3
Name		Face 6	Face 11	Face 13
Surface Type		Window	Window	Window
Construction Name		Clear Glass 3mm	Clear Glass 3mm	Clear Glass 3mm
Building Surface Name		Face 5	Face 10	Face 12
Outside Boundary Condition Object				
View Factor to Ground				
Frame and Divider Name				
Multiplier				
Number of Vertices				
Vertex 1 X-coordinate	m	-4.1	7	1.275
Vertex 1 Y-coordinate	m	2.85	-0.1	-0.4

Figure 55. Base Case Surface Details Inputs (E+).

4.1.6 Internal Gains

The zone's internal heat gain significantly impacts energy consumption as it affects indoor thermal comfort. Internal heat gain represents the heat produced within a space by various factors. Such as which is influenced by space occupants, lighting, appliances, equipment, and activities in the space. Occupant thermal comfort depends on the indoor room temperature, therefore managing internal heat gain leads to better design choices, enhances indoor thermal comfort, optimizes HVAC system sizing, and reduces energy consumption.

The study's goal is to develop the base case with realistic internal heat gains to assess their impact on the model and monitor their effects on the simulation results. All the internal heat gains in the model were illustrated in Table 4, Chapter 3, and added in this section. The first input in this section is occupancy, which allows one to select the space utilization related to the space activity schedule to calculate their heat gain (Fig. 56). The second input is the lighting system wattages each zone utilizes, related to the space utilization schedule to calculate their portion of the internal heat produced (Fig. 57). The third input is the electrical equipment and appliances utilized and assigned to their locations by zone (Fig. 58). The last input in this section is the domestic water heater supplying the three zones. In this input, a water heater with a capacity of 40 gallons was used (Fig. 59).

File Edit View New Obj Dup Obj Dup Obj + Chg Del Obj Copy Obj Paste Obj

Class List

- [.....] Site:GroundReflectance
- [.....] Site:GroundReflectance:SnowModifier
- [.....] Site:WaterMainsTemperature
- [.....] Site:Precipitation
- [.....] RoofIrrigation
- [.....] Site:SolarAndVisibleSpectrum
- [.....] Site:SpectrumData

Schedules

- [0007] Schedule:TypeLimits
- [.....] Schedule:Day:Hourly
- [0016] Schedule:Day:Interval
- [.....] Schedule:Day:List
- [0015] Schedule:Week:Daily
- [.....] Schedule:Week:Compact
- [0015] Schedule:Year
- [0008] Schedule:Compact

Comments from IDF

Explanation of Object and Current Field

Object Description: Sets internal gains and contaminant rates for occupants in the zone. If a ZoneList, SpaceList, or a Zone comprised of more than one Space is specified then this definition applies to all applicable spaces, and each instance will be named with the Space Name plus this Object Name.

Field Description: units in schedule should be fraction applied to number of people (0.0 - 1.0)
ID: A3

Field	Units	Obj1	Obj2
Name		People 3	People 2
Zone or ZoneList or Space or SpaceList Name		Thermal Zone 1	Thermal Zone 3
Number of People Schedule Name		Living Room Occ	Bedroom Occ
Number of People Calculation Method		People	People
Number of People		2	2
People per Floor Area	person/m2		
Floor Area per Person	m2/person		
Fraction Radiant		0.3	0.3
Sensible Heat Fraction		autocalculate	autocalculate
Activity Level Schedule Name		Bathroom Occ	Bathroom Occ
Carbon Dioxide Generation Rate	m3/s-W		

Figure 56. Occupancy Input (E+).

File Edit View New Obj Dup Obj Dup Obj + Chg Del Obj Copy Obj Paste Obj

Class List

- [.....] RoomAirSettings:AirflowNetwork

Internal Gains

- [0002] People
- [.....] ComfortViewFactorAngles
- [0010] Lights
- [0006] ElectricEquipment
- [.....] GasEquipment
- [0001] HotWaterEquipment
- [.....] SteamEquipment
- [.....] OtherEquipment
- [.....] ElectricEquipment:ITE:AirCooled
- [.....] ZoneBaseboard:OutdoorTemperatureControlled
- [.....] SwimmingPool:Indoor
- [.....] ZoneContaminantSourceAndSink:CarbonDioxide
- [.....] ZoneContaminantSourceAndSink:Generic:Constant
- [.....] SurfaceContaminantSourceAndSink:Generic:PressureDriver

Comments from IDF

Explanation of Object and Current Field

Object Description: Sets internal gains for lights in the zone. If a ZoneList, SpaceList, or a Zone comprised of more than one Space is specified then this definition applies to all applicable spaces, and each instance will be named with the Space Name plus this Object Name.

Field Description:
ID: A1

Field	Units	Obj1	Obj2	Obj3	Obj4	Obj5	Obj6
Name		Lights 1	Lights 2	Lights 3	Lights 4	Lights 5	Lights 6
Zone or ZoneList or Space or SpaceList Name		Thermal Zone 1	Thermal Zone 1	Thermal Zone 1	Thermal Zone 1	Thermal Zone 2	Thermal Zone 3
Schedule Name		LED light + Room	LED light + Room	LED light + Room	LED light + Room	LED light + Room	LED light + Room
Design Level Calculation Method		LightingLevel	LightingLevel	LightingLevel	LightingLevel	LightingLevel	LightingLevel
Lighting Level	W	12	12	12	12	12	12
Watts per Zone Floor Area	W/m2						
Watts per Person	W/person						
Return Air Fraction							
Fraction Radiant							
Fraction Visible							

Figure 57. Lighting System Inputs (E+).

File Edit View New Obj Dup Obj Dup Obj + Chg Del Obj Copy Obj Paste Obj

Class List

- [.....] RoomAirSettings:AirflowNetwork
- Internal Gains
 - [0002] People
 - [.....] ComfortViewFactorAngles
 - [0010] Lights
 - [0006] ElectricEquipment
 - [.....] GasEquipment
 - [0001] HotWaterEquipment
 - [.....] SteamEquipment
 - [.....] OtherEquipment
 - [.....] ElectricEquipment:ITE:AirCooled
 - [.....] ZoneBaseboard:OutdoorTemperatureControlled
 - [.....] SwimmingPool:Indoor
 - [.....] ZoneContaminantSourceAndSink:CarbonDioxide
 - [.....] ZoneContaminantSourceAndSink:Generic:Constant
 - [.....] SurfaceContaminantSourceAndSink:Generic:PressureDriver

Comments from IDF

Explanation of Object and Current Field

Object Description: Sets internal gains for electric equipment in the zone. If a ZoneList, SpaceList, or a Zone comprised of more than one Space is specified then this definition applies to all applicable spaces, and each instance will be named with the Space Name plus this Object Name.

Field Description: ID: A1

Field	Units	Obj1	Obj2	Obj3	Obj4	Obj5	Obj6
Name		Microwave	Electric Stove	TV	Refrigerator	Washer	Dryer
Zone or ZoneList or Space or SpaceList Name		Thermal Zone 1	Thermal Zone 1	Thermal Zone 1	Thermal Zone 1	Thermal Zone 1	Thermal Zone 1
Schedule Name		Microwave	Electric Stove	TV	Refrigerator	Washer	Dryer
Design Level Calculation Method		EquipmentLevel	EquipmentLevel	EquipmentLevel	EquipmentLevel	EquipmentLevel	EquipmentLevel
Design Level	W	1200	3000	50	400	400	1500
Watts per Zone Floor Area	W/m2						
Watts per Person	W/person						
Fraction Latent							
Fraction Radiant							
Fraction Lost							

Figure 58. Electrical Equipment Utilized Input (E+).

File Edit View New Obj Dup Obj Dup Obj + Chg Del Obj Copy Obj Paste Obj

Class List

- [.....] RoomAirSettings:AirflowNetwork
- Internal Gains
 - [0002] People
 - [.....] ComfortViewFactorAngles
 - [0017] Lights
 - [0006] ElectricEquipment
 - [.....] GasEquipment
 - [0001] HotWaterEquipment
 - [.....] SteamEquipment
 - [.....] OtherEquipment
 - [.....] ElectricEquipment:ITE:AirCooled
 - [.....] ZoneBaseboard:OutdoorTemperatureControlled
 - [.....] SwimmingPool:Indoor
 - [.....] ZoneContaminantSourceAndSink:CarbonDioxide
 - [.....] ZoneContaminantSourceAndSink:Generic:Constant
 - [.....] SurfaceContaminantSourceAndSink:Generic:PressureDriver

Comments from IDF

Explanation of Object and Current Field

Object Description: Sets internal gains for hot water equipment in the zone. If a ZoneList, SpaceList, or a Zone comprised of more than one Space is specified then this definition applies to all applicable spaces, and each instance will be named with the Space Name plus this Object Name.

Field Description: units in Schedule should be fraction applied to design level of hot water equipment, generally (0.0 - 1.0) ID: A3

Field	Units	Obj1
Name		Water Heater
Zone or ZoneList or Space or SpaceList Name		Thermal Zone 2
Schedule Name		Thermal Zone 1 Thermostat
Design Level Calculation Method		EquipmentLevel
Design Level	W	4500
Power per Zone Floor Area	W/m2	
Power per Person	W/person	
Fraction Latent		0
Fraction Radiant		0
Fraction Lost		0
End-Use Subcategory		General

Figure 59. Water Heater Inputs.

4.1.7 Zone HVAC Control and Thermostats

This section in E+ provides users with various HVAC control options. Zone control elements are used to manage zone temperature toward specific setpoints. The initial input in this section involves the type of control the user intends to employ in each zone. For this study, the standard method of monitoring zone temperature was chosen through the thermostat selection input. The screenshot displays the three zones of the base case, each with an assigned thermostat and their working schedule, as assigned in the previous section (Fig. 60). The second required input in this section determines the type of setpoint each zone will utilize, either single or dual setpoint for heating and cooling. The study selected the dual setpoint to set a lower temperature for the heating trigger and a higher temperature for the cooling trigger (Fig. 61).

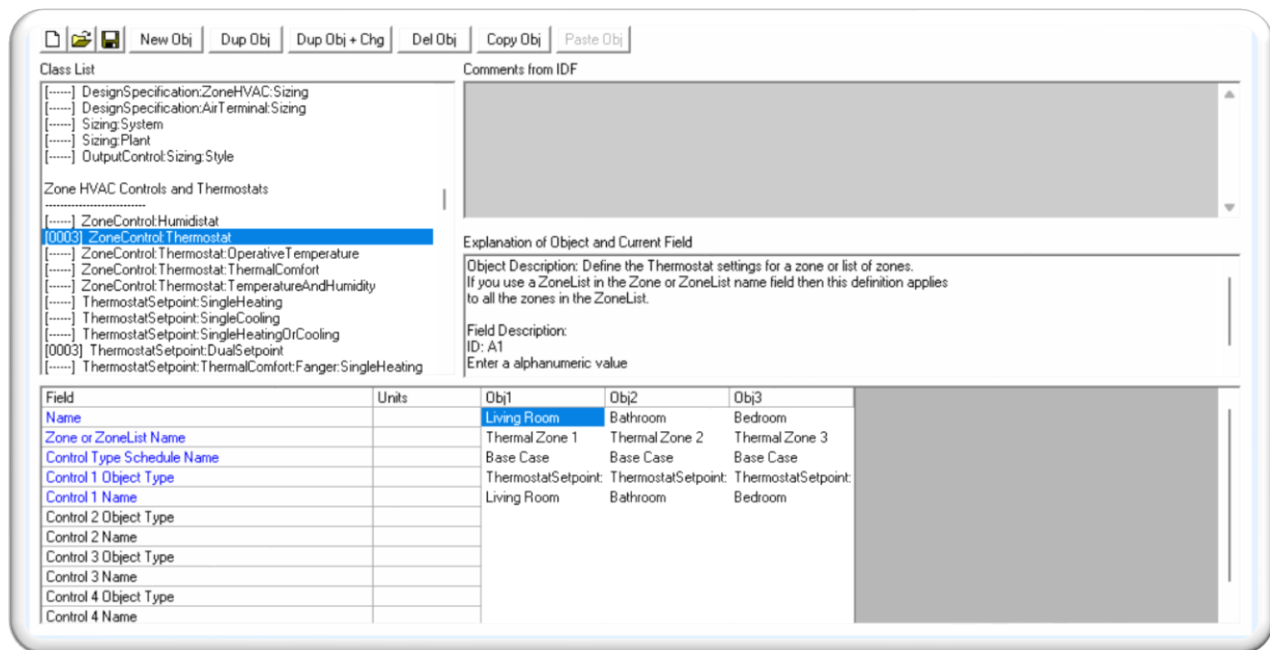


Figure 60. Zone Control Selection (E+).

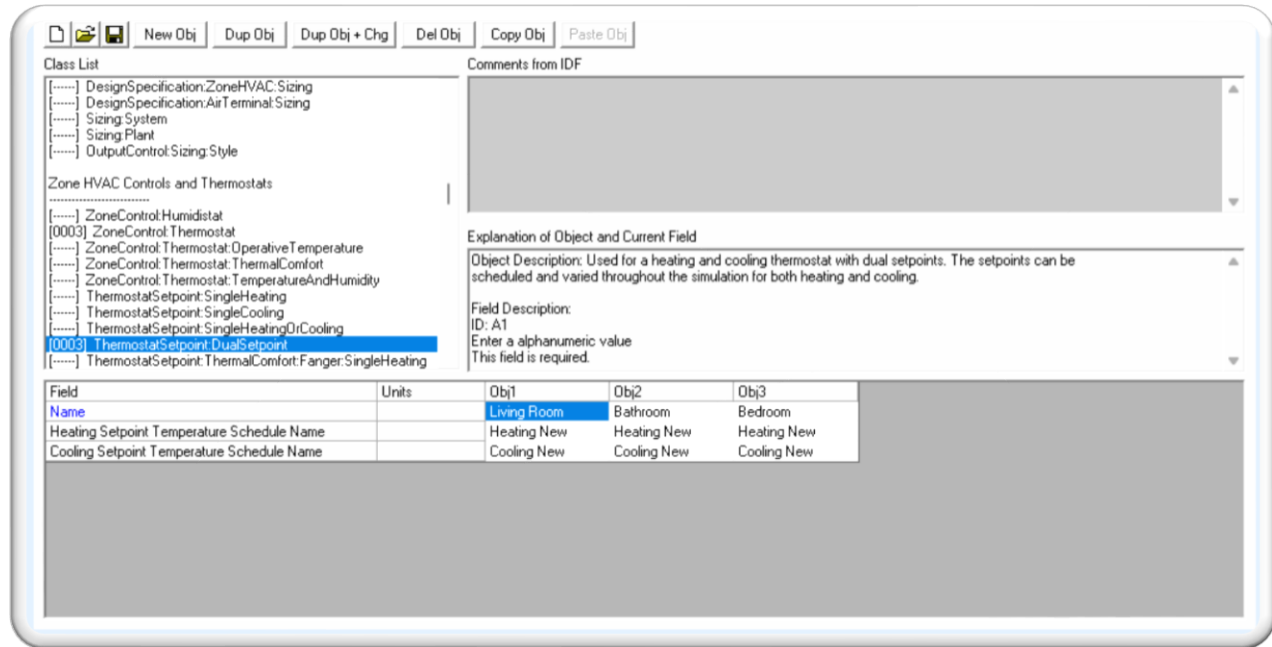


Figure 61. Thermostat Type Selection (E+).

4.1.8 Zone HVAC Forced Air Units

In this section, the user inputs the type of HVAC system utilized. In our study, as illustrated in Chapter 3, the zones are using split units according to Schedule 4. The split unit is the most common residential HVAC system used in KSA. The HVAC system is very complicated in E+ and needs to design the entire system required with the specifications. However, E+ has an option to do the calculation for the HVAC consumption all the required input is to input the zone controls, zone equipment configuration, and the ideal load zone component. The research takes advantage of using the ideal Load Air System option. The following screenshot shows the inputs added for units assigned to each zone, the assigned inputs were added to meet heating and cooling demands and the maximum flow rate accommodates peak loads. A supply air temperature of 13.0 °C enhances cooling efficiency while contributing to energy savings. Overall, these inputs are based

on HVAC design recommendations, which aim to promote comfort and efficiency. While leaving unnecessary inputs at their default settings (Fig. 62).

Class List

- Zone HVAC Forced Air Units
 - [0003] ZoneHVAC:IdealLoadsAirSystem
 - ZoneHVAC:FourPipeFanCoil
 - ZoneHVAC:WindowAirConditioner
 - ZoneHVAC:PackagedTerminalAirConditioner
 - ZoneHVAC:PackagedTerminalHeatPump
 - ZoneHVAC:WaterToAirHeatPump
 - ZoneHVAC:Dehumidifier DX
 - ZoneHVAC:EnergyRecoveryVentilator
 - ZoneHVAC:EnergyRecoveryVentilator:Controller
 - ZoneHVAC:UnitVentilator
 - ZoneHVAC:UnitHeater
 - ZoneHVAC:EvaporativeCoolerUnit
 - ZoneHVAC:HybridUnitaryHVAC
 - ZoneHVAC:OutdoorAirUnit
 - ZoneHVAC:OutdoorAirUnit:EquipmentList
 - ZoneHVAC:TerminalUnit:VariableRefrigerantFlow

Comments from IDF

Explanation of Object and Current Field

Object Description: Ideal system used to calculate loads without modeling a full HVAC system. All that is required for the ideal system are zone controls, zone equipment configurations, and the ideal loads system component. This component can be thought of as an ideal unit that mixes zone air with the specified amount of outdoor air and then adds or removes heat and moisture at 100% efficiency in order to meet the specified controls. Energy use is reported as DistrictHeating and DistrictCooling.

Field	Units	Obj1	Obj2	Obj3
Name		Living Room	Bathroom	Bedroom
Availability Schedule Name				
Zone Supply Air Node Name		Thermal Zone 1 Ide	Thermal Zone 2 Ide	Thermal Zone 3 Ide
Zone Exhaust Air Node Name				
System Inlet Air Node Name				
Maximum Heating Supply Air Temperature	C	50	50	50
Minimum Cooling Supply Air Temperature	C	13	13	13
Maximum Heating Supply Air Humidity Ratio	kgWater/kgDryA	0.0156	0.0156	0.0156
Minimum Cooling Supply Air Humidity Ratio	kgWater/kgDryA	0.0077	0.0077	0.0077
Heating Limit		NoLimit	NoLimit	NoLimit
Maximum Heating Air Flow Rate	m3/s			

Figure 62. HVAC units Input. (E+).

4.1.9 Output Reporting

In the last section, E+ provides the user with a wide range of reports about the building elements and systems, and the selection is made according to the user's preference. As illustrated in Chapter Three, the comparison metric will go through seven criteria was shown in Table 4, Chapter 3. The types of reports selected in this section are shown in (Fig 63). The research will run different types of reports on the seven metrics for data monitoring. Three types of hourly, daily, monthly, and annual were for data collection and result representations. The data representation was according to the need, the rest of the results were attached to Appendix A for the model simulation.

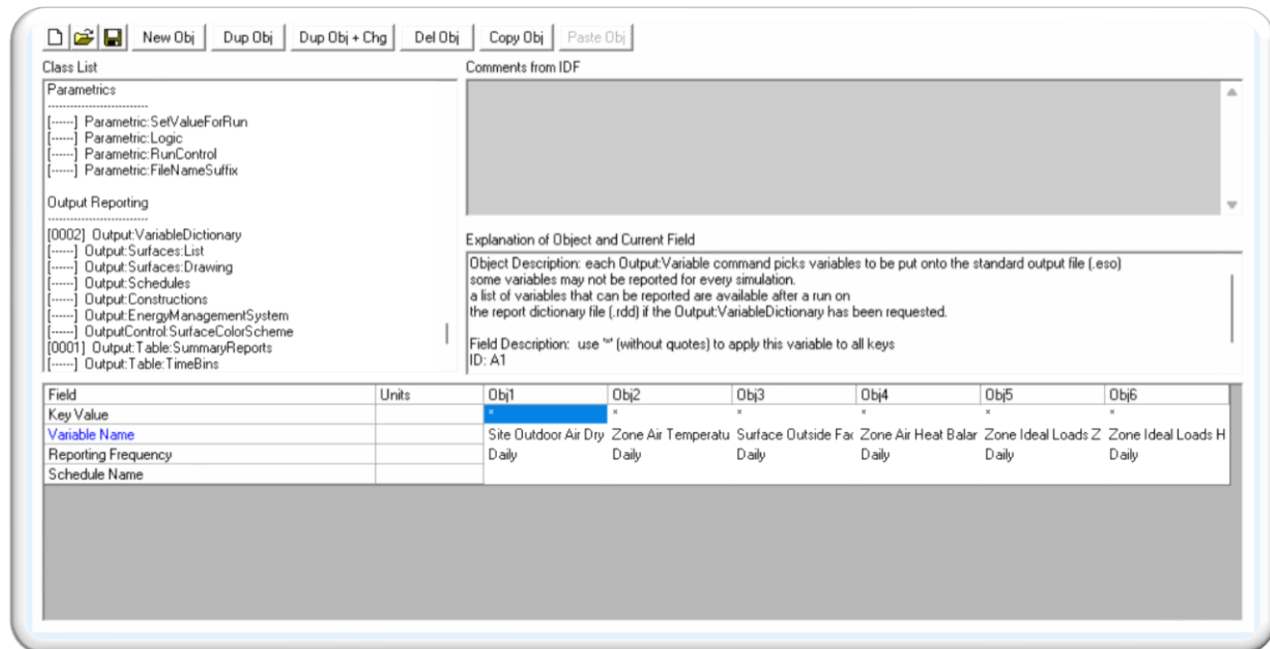


Figure 63. Output Report Selection (E+).

4.2 PCM Application

In the second phase of this chapter, the goal was to complete the study plan by developing the remaining 12 models that were utilized. In the first part of this section, the researcher adjusted the inputs of the base case model's Section 4.1.4 section (surface construction elements). The change occurred in the fourth input, which requires the layering order of building construction materials for the building elements, as demonstrated in (Fig 51). In this part, the simulation started applying PCM to find the optimum PCM location and thickness for the group models (B, C, and D). The specified thicknesses are as follows: (B1 - 0.5 cm, B2 - 1.0 cm, B3 - 1.5 cm, B4 - 2.0 cm) as shown in Figure 64, (C1 - 0.5 cm, C2- 1.0 cm, C3 - 1.5 cm, C4 - 2.0 cm) as shown in Figure 69, and (D1 - 0.5 cm, D2 - 1.0 cm, D3 - 1.5 cm, D4 - 2.0 cm) as shown in Figure 76.

4.2.1 Group B Models

Group B models were developed by applying adjustments to the study base case by adding PCM as the second layer from the outside face with different thicknesses as illustrated in (Fig 64). The adjustment applied to the base case to develop Model B1 models involves adding PCM material and placing it as the second layer from the outside face (Fig. 65). The second adjustment to create model B2 is to modify the thickness of PCM in model B1 to 1.0 cm (Fig. 66). The adjustment to create model B3 is changing the thickness of the PCM input in model B2 to 1.5 cm (Fig. 67). The last modify to create Model B4 is changing the thickness in model B3 to 2.0 cm (Fig. 68).

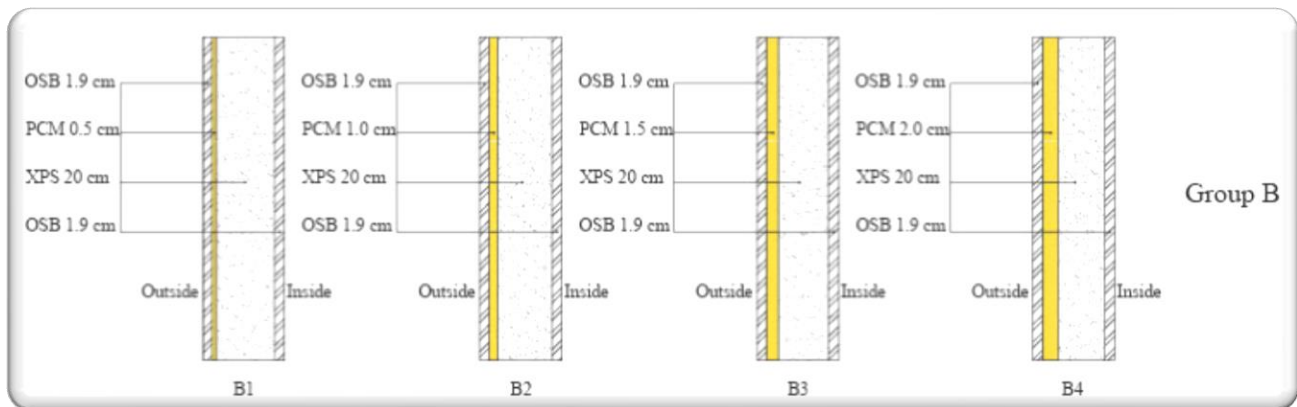


Figure 64. Wall section of Group B Models.

File Edit View New Obj Dup Obj Dup Obj + Chg Del Obj Copy Obj Paste Obj

Class List

- MaterialProperty:VariableThermalConductivity
- MaterialProperty:VariableAbsorptance
- MaterialProperty:HeatAndMoistureTransfer:Settings
- MaterialProperty:HeatAndMoistureTransfer:SorptionIsotherm
- MaterialProperty:HeatAndMoistureTransfer:Suction
- MaterialProperty:HeatAndMoistureTransfer:Redistribution
- MaterialProperty:HeatAndMoistureTransfer:Diffusion
- MaterialProperty:HeatAndMoistureTransfer:ThermalConductivity
- MaterialProperty:GlazingSpectralData
- [0005] Construction**
- Construction:CFactorUndergroundWall
- Construction:FactorGroundFloor
- ConstructionProperty:InternalHeatSource
- Construction:AirBoundary
- WindowThermalModelParams
- WindowsCalculationEngine
- Construction:ComplexFenestrationState
- Construction:WindowEquivalentLayer

Comments from IDF

Explanation of Object and Current Field

Object Description: Start with outside layer and work your way to the inside layer
Up to 10 layers total, 8 for windows
Enter the material name for each layer

Field Description:
ID: A1
Enter a alphanumeric value

Field	Units	Obj1	Obj2	Obj3	Obj4	Obj5
Name		Clear Glass 3mm	Floor	Roof	Wall	Wall Reversed
Outside Layer		CLEAR 3MM	Concrete Slab 6in	Roof Deck	OSB	OSB
Layer 2			XPS Foam	XPS Foam	25C PCM	XPS Foam
Layer 3			OSB	OSB	XPS Foam	25C PCM
Layer 4					OSB	OSB
Layer 5						
Layer 6						
Layer 7						
Layer 8						
Layer 9						
Layer 10						

Figure 65. Model B1 PCM 0.5 cm Application in the Construction Section (E+).

File Edit View New Obj Dup Obj Dup Obj + Chg Del Obj Copy Obj Paste Obj

Class List

- WindowMaterial:Screen:EquivalentLayer
- WindowMaterial:Glazing:EquivalentLayer
- WindowMaterial:Gap:EquivalentLayer
- MaterialProperty:MoisturePenetrationDepth:Settings
- MaterialProperty:PhaseChange
- [0002] MaterialProperty:PhaseChangeHysteresis**
- MaterialProperty:VariableThermalConductivity
- MaterialProperty:VariableAbsorptance
- MaterialProperty:HeatAndMoistureTransfer:Settings
- MaterialProperty:HeatAndMoistureTransfer:SorptionIsotherm
- MaterialProperty:HeatAndMoistureTransfer:Suction
- MaterialProperty:HeatAndMoistureTransfer:Redistribution
- MaterialProperty:HeatAndMoistureTransfer:Diffusion
- MaterialProperty:HeatAndMoistureTransfer:ThermalConductivity
- MaterialProperty:GlazingSpectralData
- [0005] Construction**
- Construction:CFactorUndergroundWall
- Construction:FactorGroundFloor

Comments from IDF

Explanation of Object and Current Field

Object Description: Start with outside layer and work your way to the inside layer
Up to 10 layers total, 8 for windows
Enter the material name for each layer

Field Description:
ID: A1
Enter a alphanumeric value

Field	Units	Obj1	Obj2	Obj3	Obj4	Obj5
Name		Clear Glass 3mm	Floor	Roof	Wall	Wall Reversed
Outside Layer		CLEAR 3MM	Concrete Slab 6in	Roof Deck	OSB	OSB
Layer 2			XPS Foam	XPS Foam	25C PCM	XPS Foam
Layer 3			OSB	OSB	25C PCM	25C PCM
Layer 4					XPS Foam	25C PCM
Layer 5					OSB	OSB
Layer 6						
Layer 7						
Layer 8						
Layer 9						
Layer 10						

Figure 66. Model B2 PCM Thickness Adjustment to 1.0 cm in the Construction Section (E+).

Class List

- [.....] WindowMaterial.Screen.EquivalentLayer
- [.....] WindowMaterial.Glazing.EquivalentLayer
- [.....] WindowMaterial.Gap.EquivalentLayer
- [.....] MaterialProperty:MoisturePenetrationDepth.Settings
- [.....] MaterialProperty:PhaseChange
- [0002] MaterialProperty:PhaseChangeHysteresis
- [.....] MaterialProperty:VariableThermalConductivity
- [.....] MaterialProperty:VariableAbsorptance
- [.....] MaterialProperty:HeatAndMoistureTransfer.Settings
- [.....] MaterialProperty:HeatAndMoistureTransfer.SorptionIsotherm
- [.....] MaterialProperty:HeatAndMoistureTransfer.Suction
- [.....] MaterialProperty:HeatAndMoistureTransfer.Redistribution
- [.....] MaterialProperty:HeatAndMoistureTransfer.Diffusion
- [.....] MaterialProperty:HeatAndMoistureTransfer.ThermalConductivity
- [.....] MaterialProperty:GlazingSpectralData
- [0005] Construction
- [.....] Construction:FactorUndergroundWall
- [.....] Construction:FactorGroundFloor

Comments from IDF

Explanation of Object and Current Field

Object Description: Start with outside layer and work your way to the inside layer
Up to 10 layers total, 8 for windows
Enter the material name for each layer

Field Description:
ID: A1
Enter a alphanumeric value

Field	Units	Obj1	Obj2	Obj3	Obj4	Obj5
Name		Clear Glass 3mm	Floor	Roof	Wall	Wall Reversed
Outside Layer		CLEAR 3MM	Concrete Slab 6in	Roof Deck	OSB	OSB
Layer 2			XPS Foam	XPS Foam	25C PCM	XPS Foam
Layer 3			OSB	OSB	25C PCM	25C PCM
Layer 4					25C PCM	25C PCM
Layer 5					XPS Foam	25C PCM
Layer 6					OSB	OSB
Layer 7						
Layer 8						
Layer 9						
Layer 10						

Figure 67. Model B4 PCM Thickness Adjustment to 1.5 cm in the Construction Section (E+).

Class List

- [.....] WindowMaterial.Screen.EquivalentLayer
- [.....] WindowMaterial.Glazing.EquivalentLayer
- [.....] WindowMaterial.Gap.EquivalentLayer
- [.....] MaterialProperty:MoisturePenetrationDepth.Settings
- [.....] MaterialProperty:PhaseChange
- [0002] MaterialProperty:PhaseChangeHysteresis
- [.....] MaterialProperty:VariableThermalConductivity
- [.....] MaterialProperty:VariableAbsorptance
- [.....] MaterialProperty:HeatAndMoistureTransfer.Settings
- [.....] MaterialProperty:HeatAndMoistureTransfer.SorptionIsotherm
- [.....] MaterialProperty:HeatAndMoistureTransfer.Suction
- [.....] MaterialProperty:HeatAndMoistureTransfer.Redistribution
- [.....] MaterialProperty:HeatAndMoistureTransfer.Diffusion
- [.....] MaterialProperty:HeatAndMoistureTransfer.ThermalConductivity
- [.....] MaterialProperty:GlazingSpectralData
- [0005] Construction
- [.....] Construction:FactorUndergroundWall
- [.....] Construction:FactorGroundFloor

Comments from IDF

Explanation of Object and Current Field

Object Description: Start with outside layer and work your way to the inside layer
Up to 10 layers total, 8 for windows
Enter the material name for each layer

Field Description:
ID: A1
Enter a alphanumeric value

Field	Units	Obj1	Obj2	Obj3	Obj4	Obj5
Name		Clear Glass 3mm	Floor	Roof	Wall	Wall Reversed
Outside Layer		CLEAR 3MM	Concrete Slab 6in	Roof Deck	OSB	OSB
Layer 2			XPS Foam	XPS Foam	25C PCM	XPS Foam
Layer 3			OSB	OSB	25C PCM	25C PCM
Layer 4					25C PCM	25C PCM
Layer 5					25C PCM	25C PCM
Layer 6					XPS Foam	25C PCM
Layer 7					OSB	OSB
Layer 8						
Layer 9						
Layer 10						

Figure 68. Model B3 PCM Thickness Adjustment to 2.0 cm in the Construction Section (E+).

4.2.2 Group C Models

Group C Models were developed by adding PCM in the middle of the wall construction with a variety of thicknesses as demonstrated in (Fig. 69). In this group of models the application of PCM required to be in the middle of the XPS foam layer. Thus, an adjustment to the thickness of the foam was made in the material input into the half to be added before and after the PCM layer (Fig. 70). The adjustment applied to the base case to develop model C1 is by adding PCM material first and placing it as the middle layer from the outside face (Fig. 71). The second adjustment to create model C2 is to modify the thickness of PCM in model C1 to 1.0 cm (Fig. 72). The adjustment to create model C3 involves increasing the thickness of the PCM input in model C2 to 1.5 cm (Fig. 73). The final modification to create Model C4 is increasing the thickness in model C3 to 2.0 cm (Fig. 74).

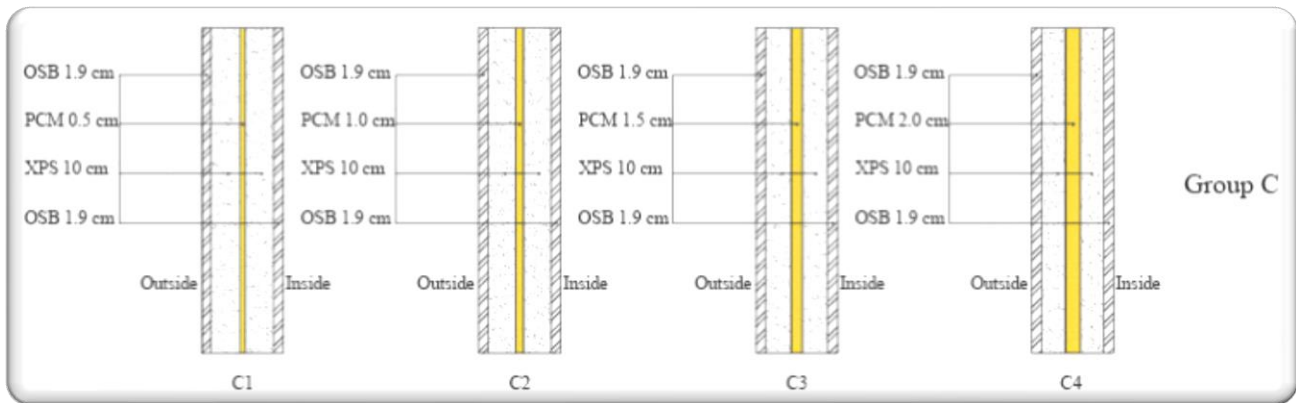


Figure 69. Wall Section of Group C Models.

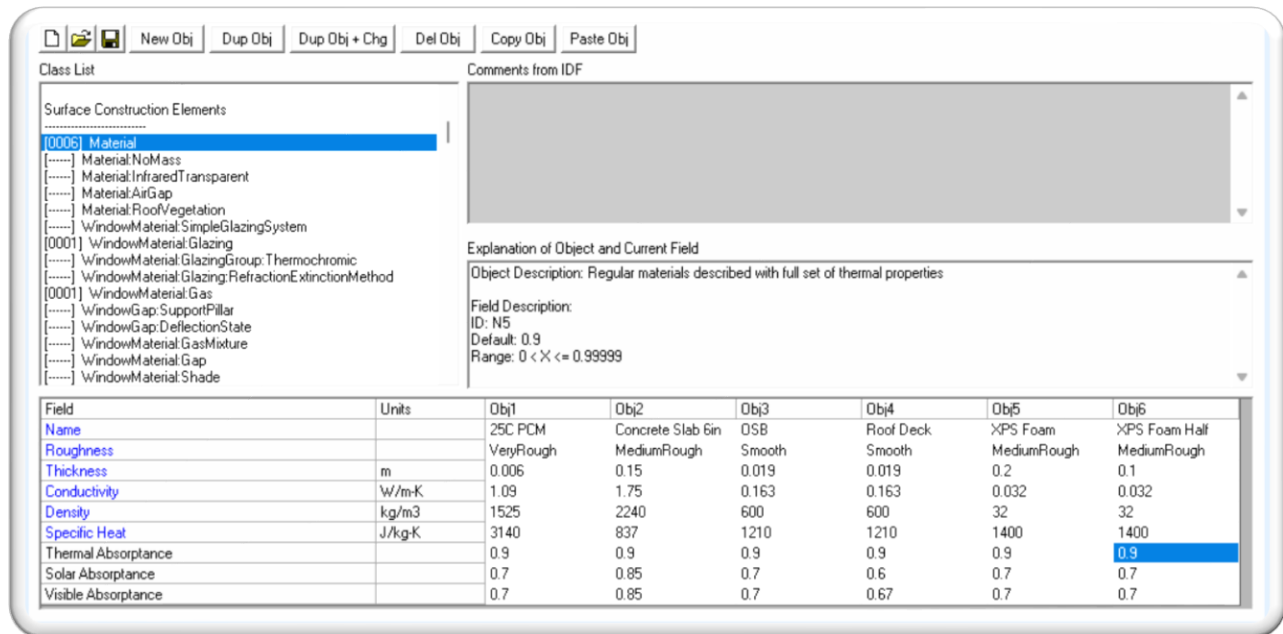


Figure 70. XPS Foam Layer Adjustment (E+).

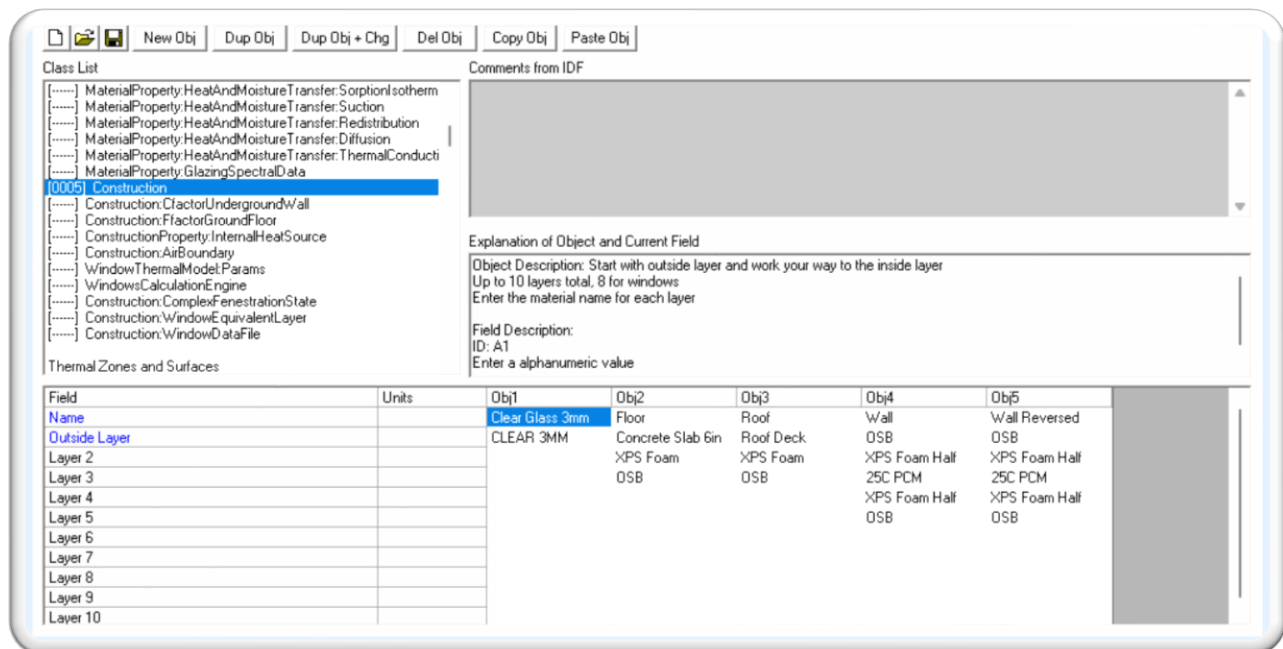


Figure 71. Model C1 PCM 0.5 cm Application in the Construction Section (E+).

Class List
 [.....] MaterialProperty:HeatAndMoistureTransfer:SorptionIsotherm
 [.....] MaterialProperty:HeatAndMoistureTransfer:Suction
 [.....] MaterialProperty:HeatAndMoistureTransfer:Redistribution
 [.....] MaterialProperty:HeatAndMoistureTransfer:Diffusion
 [.....] MaterialProperty:HeatAndMoistureTransfer:ThermalConducti
 [.....] MaterialProperty:GlazingSpectralData
[10005] Construction
 [.....] Construction:FactorUndergroundWall
 [.....] Construction:FactorGroundFloor
 [.....] ConstructionProperty:InternalHeatSource
 [.....] Construction:AirBoundary
 [.....] WindowThermalModel:Params
 [.....] WindowsCalculationEngine
 [.....] Construction:ComplexFenestrationState
 [.....] Construction:WindowEquivalentLayer
 [.....] Construction:WindowDataFile

Comments from IDF
 Explanation of Object and Current Field
 Object Description: Start with outside layer and work your way to the inside layer
 Up to 10 layers total, 8 for windows
 Enter the material name for each layer
 Field Description:
 ID: A1
 Enter an alphanumeric value

Thermal Zones and Surfaces

Field	Units	Obj1	Obj2	Obj3	Obj4	Obj5
Name		Clear Glass 3mm	Floor	Roof	Wall	Wall Reversed
Outside Layer		CLEAR 3MM	Concrete Slab 6in	Roof Deck	OSB	OSB
Layer 2			XPS Foam	XPS Foam	XPS Foam Half	XPS Foam Half
Layer 3			OSB	OSB	25C PCM	25C PCM
Layer 4					25C PCM	25C PCM
Layer 5					XPS Foam Half	XPS Foam Half
Layer 6					OSB	OSB
Layer 7						
Layer 8						
Layer 9						
Layer 10						

Figure 72. Model C3 PCM Thickness Adjustment to 1.0 cm in the Construction Section (E+).

Class List
 [.....] MaterialProperty:HeatAndMoistureTransfer:SorptionIsotherm
 [.....] MaterialProperty:HeatAndMoistureTransfer:Suction
 [.....] MaterialProperty:HeatAndMoistureTransfer:Redistribution
 [.....] MaterialProperty:HeatAndMoistureTransfer:Diffusion
 [.....] MaterialProperty:HeatAndMoistureTransfer:ThermalConducti
 [.....] MaterialProperty:GlazingSpectralData
[10005] Construction
 [.....] Construction:FactorUndergroundWall
 [.....] Construction:FactorGroundFloor
 [.....] ConstructionProperty:InternalHeatSource
 [.....] Construction:AirBoundary
 [.....] WindowThermalModel:Params
 [.....] WindowsCalculationEngine
 [.....] Construction:ComplexFenestrationState
 [.....] Construction:WindowEquivalentLayer
 [.....] Construction:WindowDataFile

Comments from IDF
 Explanation of Object and Current Field
 Object Description: Start with outside layer and work your way to the inside layer
 Up to 10 layers total, 8 for windows
 Enter the material name for each layer
 Field Description:
 ID: A1
 Enter an alphanumeric value

Thermal Zones and Surfaces

Field	Units	Obj1	Obj2	Obj3	Obj4	Obj5
Name		Clear Glass 3mm	Floor	Roof	Wall	Wall Reversed
Outside Layer		CLEAR 3MM	Concrete Slab 6in	Roof Deck	OSB	OSB
Layer 2			XPS Foam	XPS Foam	XPS Foam Half	XPS Foam Half
Layer 3			OSB	OSB	25C PCM	25C PCM
Layer 4					25C PCM	25C PCM
Layer 5					25C PCM	25C PCM
Layer 6					XPS Foam Half	XPS Foam Half
Layer 7					OSB	OSB
Layer 8						
Layer 9						
Layer 10						

Figure 73. Model C3 PCM Thickness Adjustment to 1.5 cm in the Construction Section (E+).

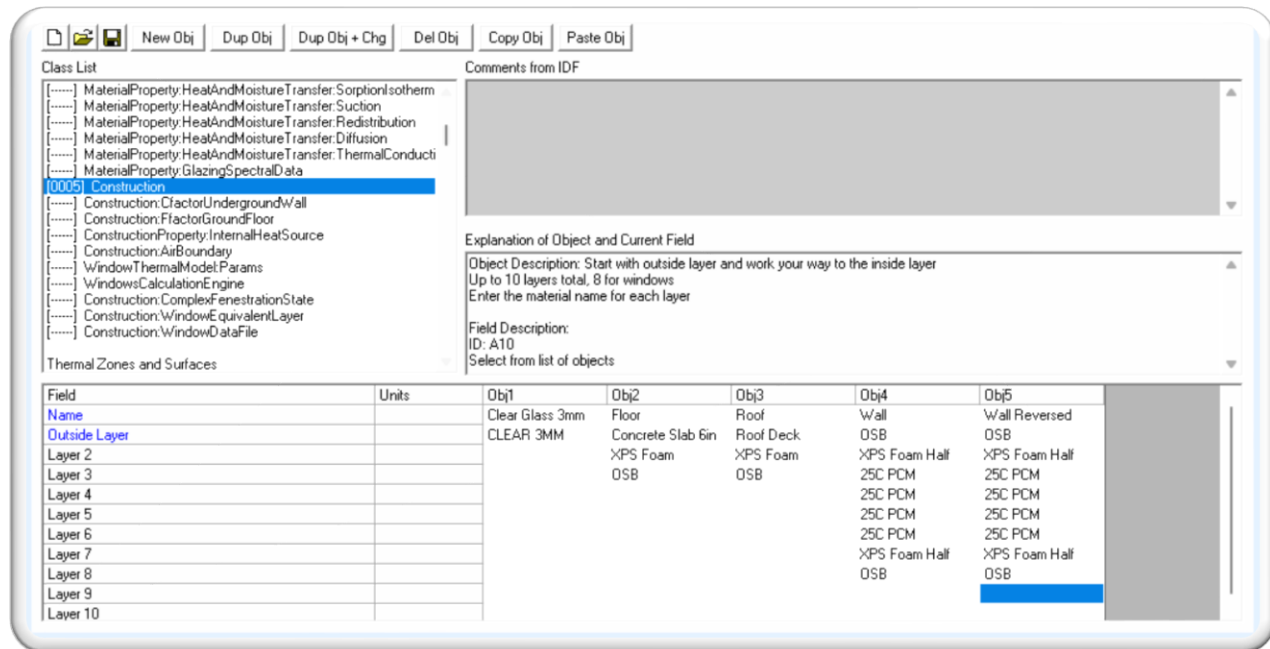


Figure 74. Model C3 PCM Thickness Adjustment to 2.0 cm in the Construction Section (E+).

4.2.3 Group D Models

Group D Models were developed by applying adjustments to the study base case, adding PCM as the second layer from the inside face with different thicknesses as shown in (Fig. 75). In this section, the XPS foam layer was returned to its original thickness since the PCM layer in this group is placed after the interior face (Fig. 76). The adjustment applied to the base case to develop model D1 involves adding PCM material first and placing it as the second layer from the outside face (Fig. 77). The second adjustment to create model D2 was to modify the thickness of PCM in model D1 to 1.0 cm (Fig. 78). The adjustment to create model D3 was changing the thickness of the PCM input in model D2 to 1.5 cm (Fig. 79). The final modification to create Model D4 was changing the thickness in model D3 to 2.0 cm (Fig. 80).

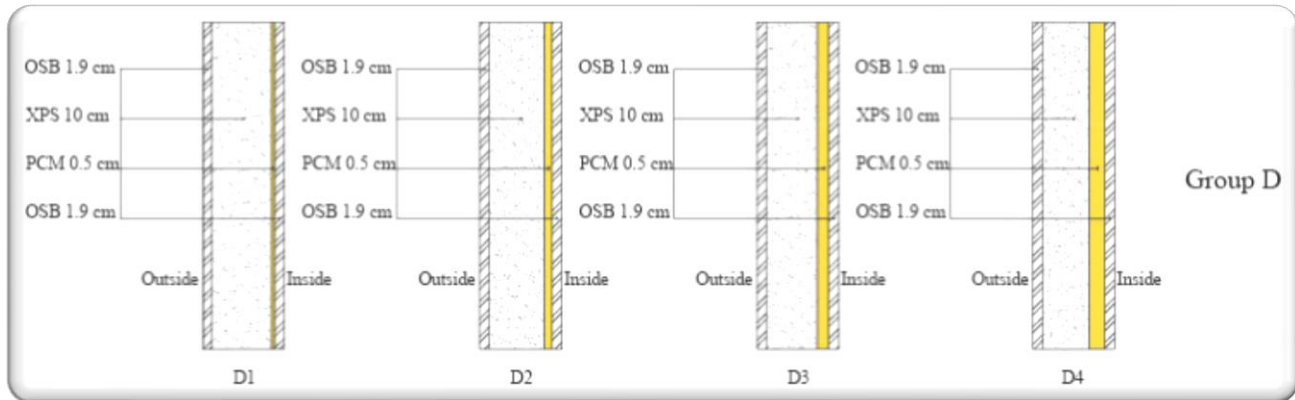


Figure 75. Wall Section of Group D Models.

Class List

Surface Construction Elements

- [0005] Material
- [.....] Material:NoMass
- [.....] Material:InfraredTransparent
- [.....] Material:AirGap
- [.....] Material:RoofVegetation
- [.....] WindowMaterial:SimpleGlazingSystem
- [0001] WindowMaterial:Glazing
- [.....] WindowMaterial:GlazingGroup:Thermochromic
- [.....] WindowMaterial:Glazing:RefractionExtinctionMethod
- [0001] WindowMaterial:Gas
- [.....] WindowGap:SupportPillar
- [.....] WindowGap:DeflectionState
- [.....] WindowMaterial:GasMixture
- [.....] WindowMaterial:Gap
- [.....] WindowMaterial:Shade

Comments from IDF

Explanation of Object and Current Field

Object Description: Regular materials described with full set of thermal properties

Field Description:
ID: A1
Enter a alphanumeric value
This field is required.

Field	Units	Obj1	Obj2	Obj3	Obj4	Obj5
Name		25C PCM	Concrete Slab 6in	OSB	Roof Deck	XPS Foam
Roughness		VeryRough	MediumRough	Smooth	Smooth	MediumRough
Thickness	m	0.006	0.15	0.019	0.019	0.2
Conductivity	W/m-K	1.09	1.75	0.163	0.163	0.032
Density	kg/m3	1525	2240	600	600	32
Specific Heat	J/kg-K	3140	837	1210	1210	1400
Thermal Absorptance		0.9	0.9	0.9	0.9	0.9
Solar Absorptance		0.7	0.85	0.7	0.6	0.7
Visible Absorptance		0.7	0.85	0.7	0.67	0.7

Figure 76. XPS Foam Thickness Recovering (E+).

Class List

- MaterialProperty:VariableThermalConductivity
- MaterialProperty:VariableAbsorptance
- MaterialProperty:HeatAndMoistureTransfer:Settings
- MaterialProperty:HeatAndMoistureTransfer:SorptionIsotherm
- MaterialProperty:HeatAndMoistureTransfer:Suction
- MaterialProperty:HeatAndMoistureTransfer:Redistribution
- MaterialProperty:HeatAndMoistureTransfer:Diffusion
- MaterialProperty:HeatAndMoistureTransfer:ThermalConductivity
- MaterialProperty:GlazingSpectralData
- 10005 Construction**
- Construction:FactorUndergroundWall
- Construction:FactorGroundFloor
- ConstructionProperty:InternalHeatSource
- Construction:AirBoundary
- WindowThermalModel:Params
- WindowsCalculation:Engine
- Construction:ComplexFenestrationState
- Construction:WindowEquivalentLayer

Comments from IDF

Explanation of Object and Current Field

Object Description: Start with outside layer and work your way to the inside layer
Up to 10 layers total, 8 for windows
Enter the material name for each layer

Field Description:
ID: A7
Select from list of objects

Field	Units	Obj1	Obj2	Obj3	Obj4	Obj5
Name		Clear Glass 3mm	Floor	Roof	Wall	Wall Reversed
Outside Layer		CLEAR 3MM	Concrete Slab 6in	Roof Deck	OSB	OSB
Layer 2			XPS Foam	XPS Foam	XPS Foam	25C PCM
Layer 3			OSB	OSB	25C PCM	XPS Foam
Layer 4					OSB	OSB
Layer 5						
Layer 6						
Layer 7						
Layer 8						
Layer 9						
Layer 10						

Figure 77. Model D1 PCM Thickness Adjustment to 0.5 cm in the Construction Section (E+).

Class List

- MaterialProperty:VariableThermalConductivity
- MaterialProperty:VariableAbsorptance
- MaterialProperty:HeatAndMoistureTransfer:Settings
- MaterialProperty:HeatAndMoistureTransfer:SorptionIsotherm
- MaterialProperty:HeatAndMoistureTransfer:Suction
- MaterialProperty:HeatAndMoistureTransfer:Redistribution
- MaterialProperty:HeatAndMoistureTransfer:Diffusion
- MaterialProperty:HeatAndMoistureTransfer:ThermalConductivity
- MaterialProperty:GlazingSpectralData
- 10005 Construction**
- Construction:FactorUndergroundWall
- Construction:FactorGroundFloor
- ConstructionProperty:InternalHeatSource
- Construction:AirBoundary
- WindowThermalModel:Params
- WindowsCalculation:Engine
- Construction:ComplexFenestrationState
- Construction:WindowEquivalentLayer

Comments from IDF

Explanation of Object and Current Field

Object Description: Start with outside layer and work your way to the inside layer
Up to 10 layers total, 8 for windows
Enter the material name for each layer

Field Description:
ID: A1
Enter an alphanumeric value

Field	Units	Obj1	Obj2	Obj3	Obj4	Obj5
Name		Clear Glass 3mm	Floor	Roof	Wall	Wall Reversed
Outside Layer		CLEAR 3MM	Concrete Slab 6in	Roof Deck	OSB	OSB
Layer 2			XPS Foam	XPS Foam	XPS Foam	25C PCM
Layer 3			OSB	OSB	25C PCM	25C PCM
Layer 4					25C PCM	XPS Foam
Layer 5					OSB	OSB
Layer 6						
Layer 7						
Layer 8						
Layer 9						
Layer 10						

Figure 78. Model D2 PCM Thickness Adjustment to 1.0 cm in the Construction Section (E+).

Class List

- MaterialProperty:VariableThermalConductivity
- MaterialProperty:VariableAbsorptance
- MaterialProperty:HeatAndMoistureTransfer:Settings
- MaterialProperty:HeatAndMoistureTransfer:SorptionIsotherm
- MaterialProperty:HeatAndMoistureTransfer:Suction
- MaterialProperty:HeatAndMoistureTransfer:Redistribution
- MaterialProperty:HeatAndMoistureTransfer:Diffusion
- MaterialProperty:HeatAndMoistureTransfer:ThermalConducti
- MaterialProperty:GlazingSpectralData
- 10005 Construction**
- Construction:FactorUndergroundWall
- Construction:FactorGroundFloor
- ConstructionProperty:InternalHeatSource
- Construction:AirBoundary
- WindowThermalModelParams
- WindowsCalculationEngine
- Construction:ComplexFenestrationState
- Construction:WindowEquivalentLayer

Comments from IDF

Explanation of Object and Current Field

Object Description: Start with outside layer and work your way to the inside layer
Up to 10 layers total, 8 for windows
Enter the material name for each layer

Field Description:
ID: A1
Enter a alphanumeric value

Field	Units	Obj1	Obj2	Obj3	Obj4	Obj5
Name		Clear Glass 3mm	Floor	Roof	Wall	Wall Reversed
Outside Layer		CLEAR 3MM	Concrete Slab 6in	Roof Deck	OSB	OSB
Layer 2			XPS Foam	XPS Foam	XPS Foam	25C PCM
Layer 3			OSB	OSB	25C PCM	25C PCM
Layer 4					25C PCM	25C PCM
Layer 5					25C PCM	XPS Foam
Layer 6					OSB	OSB
Layer 7						
Layer 8						
Layer 9						
Layer 10						

Figure 79. Model D3 PCM Thickness Adjustment to 1.5 cm in the Construction Section (E+).

Class List

- MaterialProperty:VariableThermalConductivity
- MaterialProperty:VariableAbsorptance
- MaterialProperty:HeatAndMoistureTransfer:Settings
- MaterialProperty:HeatAndMoistureTransfer:SorptionIsotherm
- MaterialProperty:HeatAndMoistureTransfer:Suction
- MaterialProperty:HeatAndMoistureTransfer:Redistribution
- MaterialProperty:HeatAndMoistureTransfer:Diffusion
- MaterialProperty:HeatAndMoistureTransfer:ThermalConducti
- MaterialProperty:GlazingSpectralData
- 10005 Construction**
- Construction:FactorUndergroundWall
- Construction:FactorGroundFloor
- ConstructionProperty:InternalHeatSource
- Construction:AirBoundary
- WindowThermalModelParams
- WindowsCalculationEngine
- Construction:ComplexFenestrationState
- Construction:WindowEquivalentLayer

Comments from IDF

Explanation of Object and Current Field

Object Description: Start with outside layer and work your way to the inside layer
Up to 10 layers total, 8 for windows
Enter the material name for each layer

Field Description:
ID: A1
Enter a alphanumeric value

Field	Units	Obj1	Obj2	Obj3	Obj4	Obj5
Name		Clear Glass 3mm	Floor	Roof	Wall	Wall Reversed
Outside Layer		CLEAR 3MM	Concrete Slab 6in	Roof Deck	OSB	OSB
Layer 2			XPS Foam	XPS Foam	XPS Foam	25C PCM
Layer 3			OSB	OSB	25C PCM	25C PCM
Layer 4					25C PCM	25C PCM
Layer 5					25C PCM	25C PCM
Layer 6					25C PCM	XPS Foam
Layer 7					OSB	OSB
Layer 8						
Layer 9						
Layer 10						

Figure 80. Model D3 PCM Thickness Adjustment to 1.5 cm in the Construction Section (E+).

This chapter aims to demonstrate the development of the study simulation models respectively and to illustrate the process step by step. The first model was developed is model A as the study base case with no PCM applied. The next step involves adjusting the base case to create study models B, C, and D, with PCM applied. The chapter delivers through demonstration the necessary details and inputs about the models as required in E+. The investigation to develop these research models went through modifications to simulate the differences in PCM thickness and application. The categorization and data reporting required for the study to proceed were covered. The obtained data will be used in the LCCA study in the following chapter.

Chapter 5: Simulation Results and Discussion

The simulation results were collected in groups for comparison with the base case model. Initially, the results will be presented and discussed in each group presentation. The first section will showcase the base case simulation results, validating them by comparing them with a similar example from Riyadh. The second step involves presenting the comparison between group B and the base case results, nominating the model with the highest savings as the optimum in the group. Subsequent sections will demonstrate the results for groups C and D, comparing them to the base case and selecting the optimum model from both groups. Finally, the three nominated models will be compared.

5.1 Base Case Results

The base case simulation results were obtained from the first run of the simulation, showing a total site energy for the entire year of 124.2 GJ (34,513kWh). The monthly energy utilization reveals that the highest consumption period throughout the year occurs from May to November, with August having the highest at 13 GJ. The lowest consumption is observed from December to May, with December having the lowest at 8 GJ (Fig. 81).

Overall, the summer season presented the highest energy consumption throughout the year, spanning from May to October. The winter season's consumption results weren't as high compared to the summer season. The breakdown of monthly results has revealed the impact of cooling loads, significantly increasing the total energy used during the hot summer season (Fig. 81). The breakdown for the months from May to October has shown that cooling energy represents 80% of the total monthly consumption. The winter season has lower energy consumption since the cooling mode is mostly off, given that the thermostat setpoint trigger is not met for many operational hours.

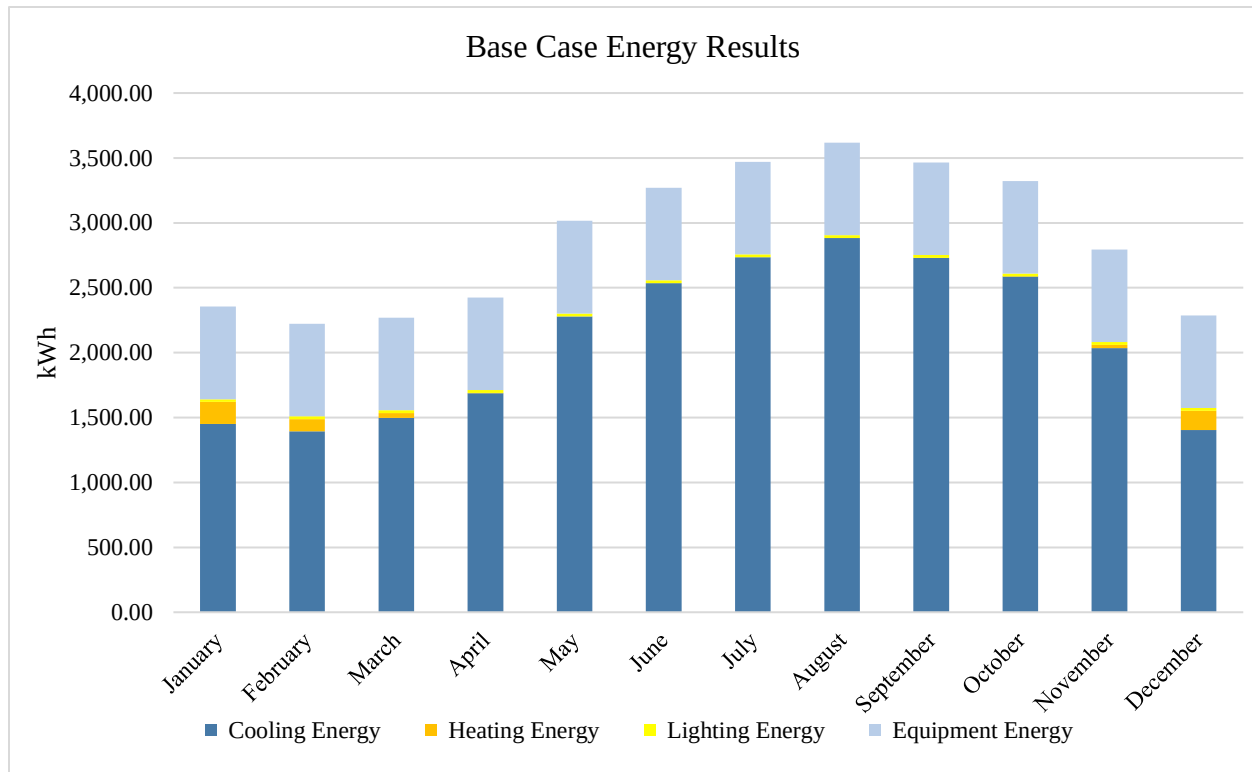


Figure 81. Model A Simulation Results: illustrate monthly energy consumption.

5.1.1 Results Validation

The study compared the base case results with a similar example from Riyadh to validate the simulation results. The electricity bills from a similar apartment in Riyadh city were collected for a unit with about the same square footage. The results were then used to establish an average Energy Use Intensity (EUI) to assess the accuracy of the findings or to establish an EUI average if significant variations were present. The example is an apartment in a residential building on the second floor with an exposed roof and an area of 65 m² (699 ft²) and is occupied by a young couple. The annual energy consumption values for this example were collected from the resident portal on the Saudi Electricity Company website (Fig. 82).

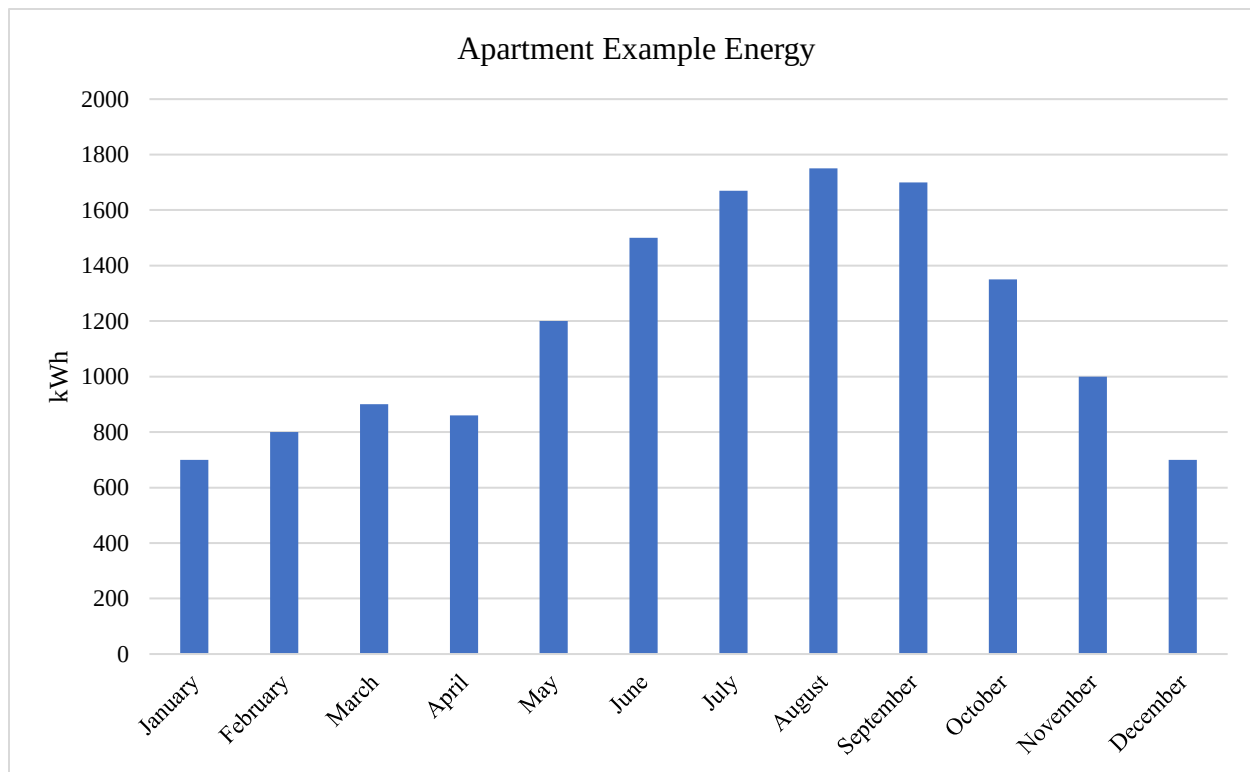


Figure 82. Apartment Monthly Energy Consumption.

The comparison between the example apartment and the study base case has revealed a significant monthly difference in energy consumption (Table 6). The apartment has an annual total site energy of 50 GJ (14,130 kWh) while the base case has 124 GJ (34,513 kWh). The result of the site energy consumption comparison has shown an average difference of 83.8% between the base case and the apartment. The apartment has an EUI average of 217 kWh/m²/year (20 kWh/ft²/year), while the EUI for the base case model is 728 kWh/m²/year (67 kWh/ft²/year).

Table 6. The table contains the monthly electricity consumption details for the Base case model A and the Apartment for comparison.

Month	Example Monthly Energy Consumption (kWh)	Bill Cost in Saudi Rials	Base Case Monthly Energy Consumption (kWh)	Bill Cost in Saudi Rials
Jan,	700	126	2,354	423
Feb,	800	162	2,222	400
Mar,	900	162	2,269	408
Apr,	860	154	2,424	436
May,	1200	207	3,015	542
Jun,	1500	279	3,270	588
Jul,	1670	252	3,469	624
Aug,	1750	315	3,618	651
Sep,	1700	306	3,464	623
Oct,	1350	243	3,322	598
Nov,	1000	180	2,793	502
Dec,	700	126	2,287	411
Total	14,130	2,745	34,513	6,212

The large difference between the simulation results and the apartment was considered unreasonable and highlighted an issue with the reliability of the base case (Fig. 83). Subsequently, a series of troubleshooting steps were conducted because two issues were found in the simulation results:

First, the energy simulation of the base case revealed an unexpected monthly energy pattern. Instead of the anticipated gradual increase in energy consumption from January to summer, the results showed unusually high energy usage in January and April during the winter, while February and March, which typically have higher outdoor temperatures, showed lower consumption. The rest of the months followed the expected pattern.

Second, the base case simulation was expected to match the apartment's energy consumption due to their similar size and climate. However, differences such as continuous HVAC operation in the base case, an electric stove, larger windows, and a conditioned bathroom led to variations. Several adjustments were made to the model to better match the apartment's characteristics, which significantly reduced total site energy. A detailed explanation of the problem-solving process is provided in the following sections.

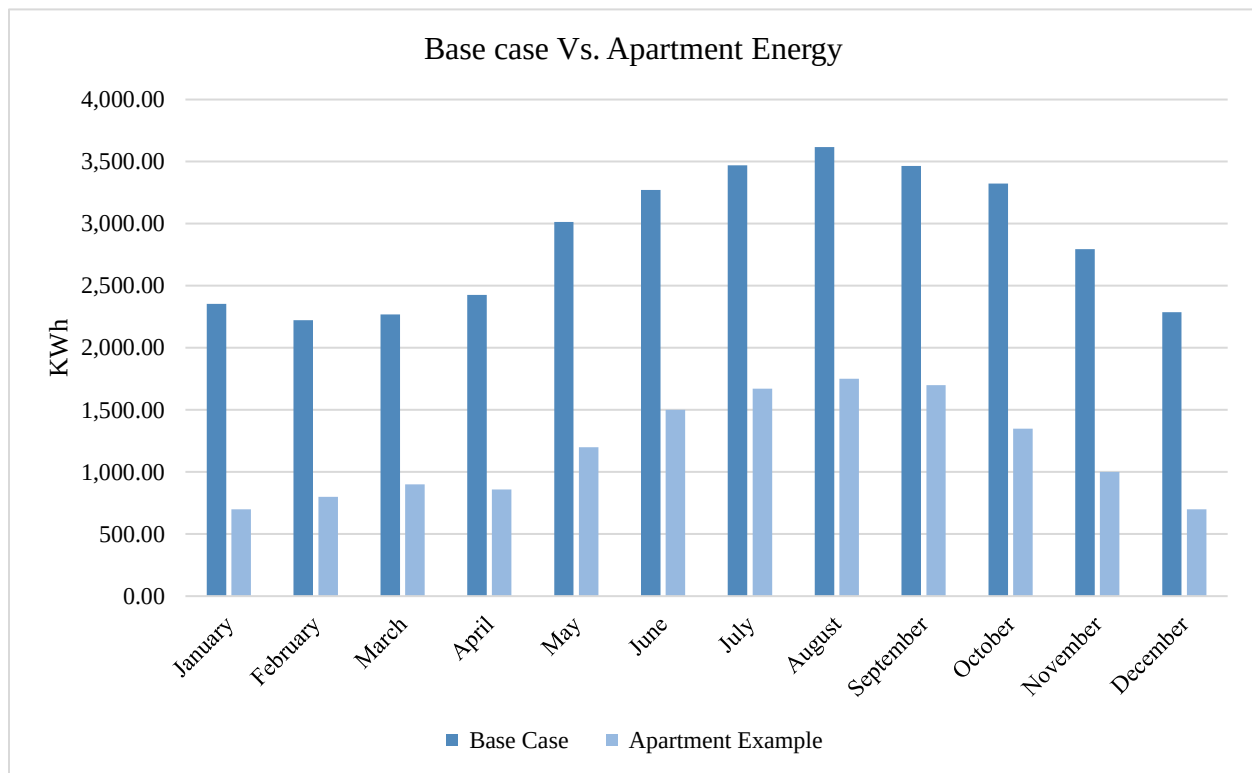


Figure 83. Visualizing Simulation and Apartment Energy Usage.

5.1.2 Energy Consumption Pattern Explanation

The energy simulation of the base case has shown a different monthly energy pattern. The expected energy pattern was to match the apartment example's monthly pattern, which should be low starting from January and show minor monthly increases toward the summer season as the hot season begins, followed by a decrease after August as the winter season approaches, as the apartment example showed (Fig. 83). However, the base case simulation results have shown an unusual energy consumption pattern, with higher energy consumption in January and April during the winter season than in February and March, which are expected to have higher outdoor temperatures, while the rest of the month's energy consumption has shown a normal pattern as expected (Fig. 84).

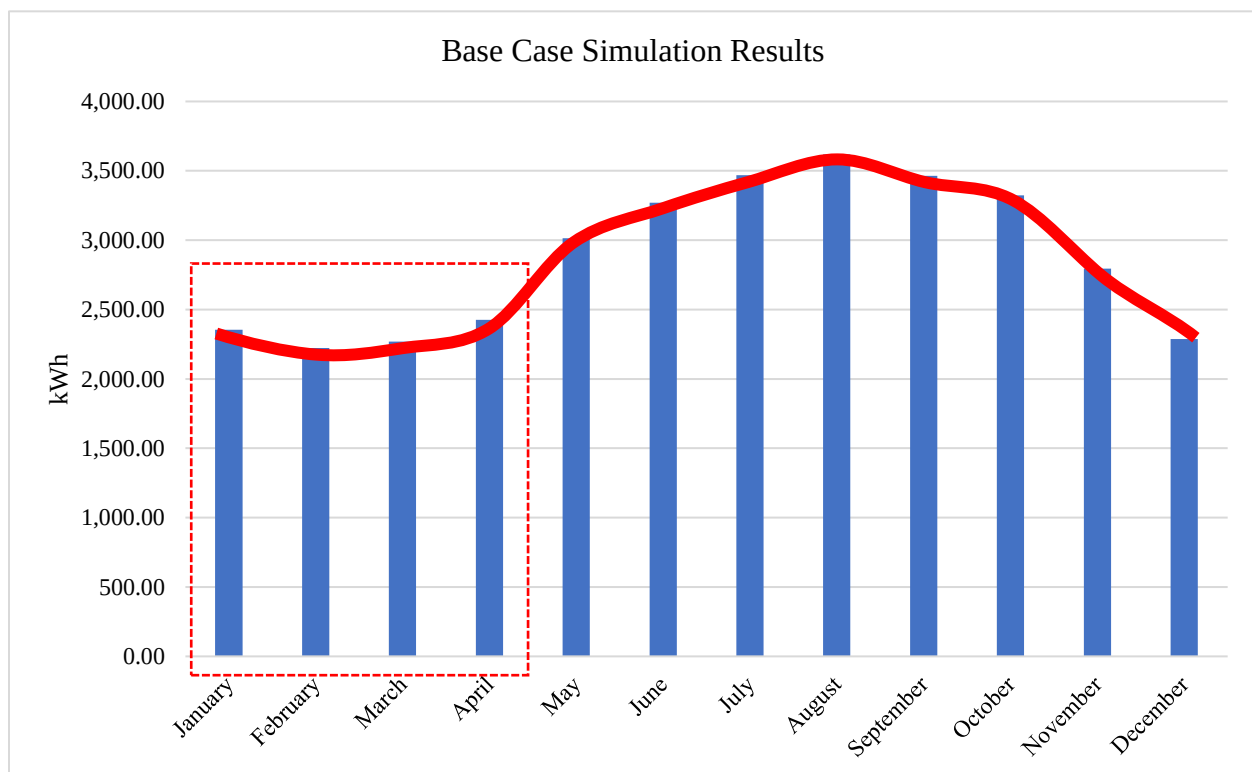


Figure 84. Energy Consumption Monthly Pattern.

The simulation results might be higher or lower than the apartment example which could be justified. The monthly energy patterns are expected to closely match since the data sets are for the same climatic condition which should be reflected in the apartment energy consumption patterns (Fig. 85). Thus, the pattern difference suggests the need for further investigation to understand the reason for the change and provide more insight and justification for its occurrence for the model validation.

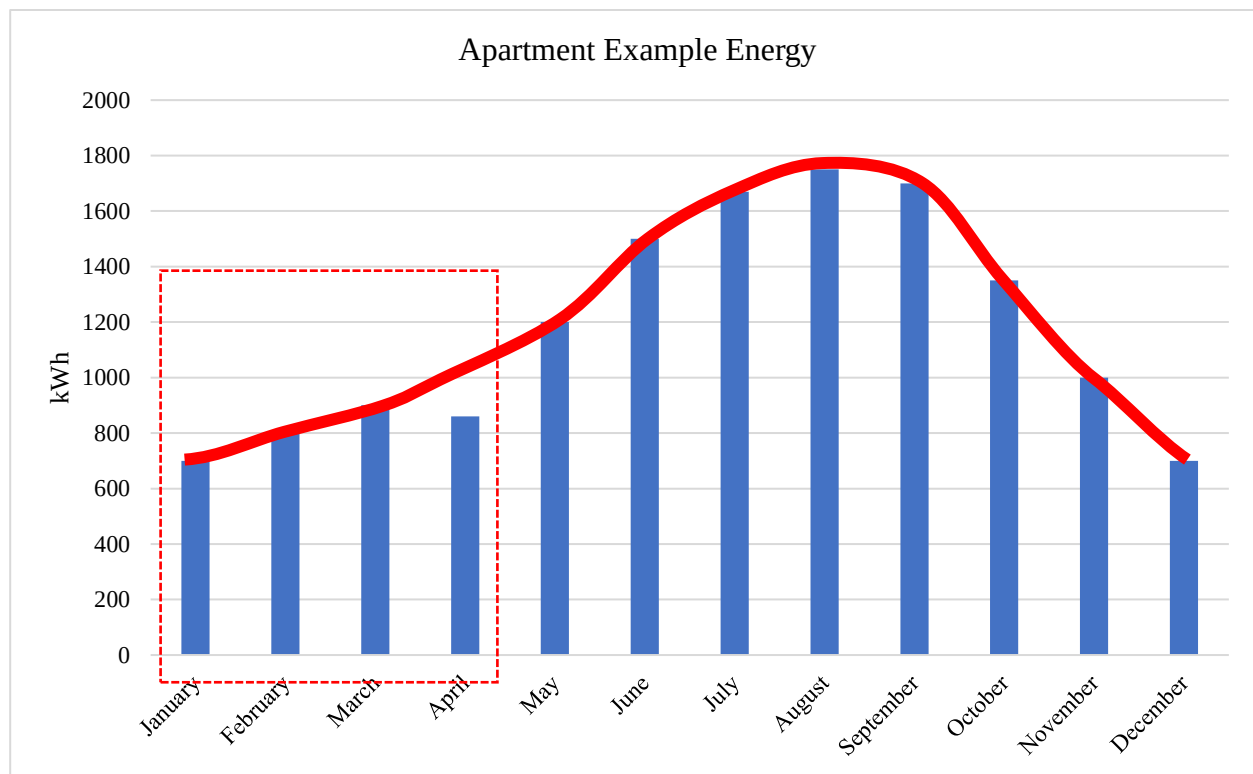


Figure 85. Apartment Example Energy Pattern.

The first troubleshooting step was to investigate if this pattern is unique to the SIPs' thermal performance. For this, the wall construction for the base case was modified to represent the typical building materials used in KSA and to match the apartment wall assembly. The following layers (Plaster, Brick, Plaster) were used to add thermal mass to the wall structure, while all other inputs

were maintained (Fig. 86 & 87). The simulation results were visualized to compare with the SIPs panels' base case energy pattern to conclude whether it matched or not.

Class List

- [.....] Schedule:Week:Compact
- [0017] Schedule:Year
- [0008] Schedule:Compact
- [0007] Schedule:Constant
- [.....] Schedule:File:Shading
- [.....] Schedule:File

Surface Construction Elements

- [0009] Material
- [.....] Material:NoMass
- [.....] Material:InfraredTransparent
- [.....] Material:AirGap
- [.....] Material:RoofVegetation
- [.....] WindowMaterial:SimpleGlazingSystem
- [0001] WindowMaterial:Glazing
- [.....] WindowMaterial:GlazingGroup:Thermochromic
- [.....] WindowMaterial:Glazing:RefractionExtinctionMethod

Comments from IDF

Explanation of Object and Current Field

Object Description: Regular materials described with full set of thermal properties

Field Description:
ID: A1
Enter a alphanumeric value
This field is required.

Field	Units	Obj1	Obj2	Obj3	Obj4	Obj5	Obj6	
Name		XPS Foam Half	25C PCM	Brick	Insulation	Plaster	Concrete Slab 6in	0
Roughness		MediumRough	VeryRough	Rough	MediumRough	Smooth	MediumRough	S
Thickness	m	0.075	0.005	0.2	0.1	0.02	0.15	0
Conductivity	W/m-K	0.032	1.1445	0.81	0.03	0.68	1.75	0
Density	kg/m3	32	1525	1600	30	1525	2240	6
Specific Heat	J/kg-K	1400	3140	840	840	840	837	1
Thermal Absorptance		0.9	0.9	0.9	0.9	0.9	0.9	0
Solar Absorptance		0.7	0.7	0.7	0.7	0.7	0.85	0
Visible Absorptance		0.7	0.7	0.7	0.7	0.7	0.85	0

Figure 86. E+ Material Properties.

Class List

- [.....] WindowMaterial:Glazing:EquivalentLayer
- [.....] WindowMaterial:Gap:EquivalentLayer
- [.....] MaterialProperty:MoisturePenetrationDepth:Settings
- [.....] MaterialProperty:PhaseChange
- [0001] MaterialProperty:PhaseChangeHysteresis
- [.....] MaterialProperty:VariableThermalConductivity
- [.....] MaterialProperty:VariableAbsorptance
- [.....] MaterialProperty:HeatAndMoistureTransfer:Settings
- [.....] MaterialProperty:HeatAndMoistureTransfer:SorptionIsotherm
- [.....] MaterialProperty:HeatAndMoistureTransfer:Suction
- [.....] MaterialProperty:HeatAndMoistureTransfer:Redistribution
- [.....] MaterialProperty:HeatAndMoistureTransfer:Diffusion
- [.....] MaterialProperty:HeatAndMoistureTransfer:ThermalConductivity
- [.....] MaterialProperty:GlazingSpectralData
- [0005] Construction
- [.....] Construction:FactorUndergroundWall
- [.....] Construction:FactorGroundFloor
- [.....] ConstructionProperty:InternalHeatSource

Comments from IDF

Explanation of Object and Current Field

Object Description: Start with outside layer and work your way to the inside layer
Up to 10 layers total, 8 for windows
Enter the material name for each layer

Field Description:
ID: A1
Enter a alphanumeric value

Field	Units	Obj1	Obj2	Obj3	Obj4	Obj5
Name		Clear Glass 3mm	Floor	Roof	Wall	Wall Reversed
Outside Layer		CLEAR 3MM	Concrete Slab 6in	Roof Deck	Plaster	Plaster
Layer 2			XPS Foam	XPS Foam	Brick	Brick
Layer 3			OSB	OSB	Plaster	Plaster
Layer 4						
Layer 5						
Layer 6						
Layer 7						
Layer 8						
Layer 9						
Layer 10						

Figure 87. Brick Structure Application E+

The simulation results show that the thermal performance of the SIPs, in general, is better than the brick, lowering the total site energy by 9%. However, the comparison after applying the brick wall structure showed a minor change in the energy pattern in the winter (Fig. 88) but still was not the pattern expected. This provided insight into the differences in thermal performance for the two assemblies. The simulation results revealed the following: SIPs have high thermal performance in the hot season and lower thermal performance in the cold season when compared to the brick assembly. The performance of the brick walls was better in the cold season since it utilizes the thermal mass effect for warm days and cold nights, while its performance was lower during the cooling season when nighttime temperatures remained relatively high.

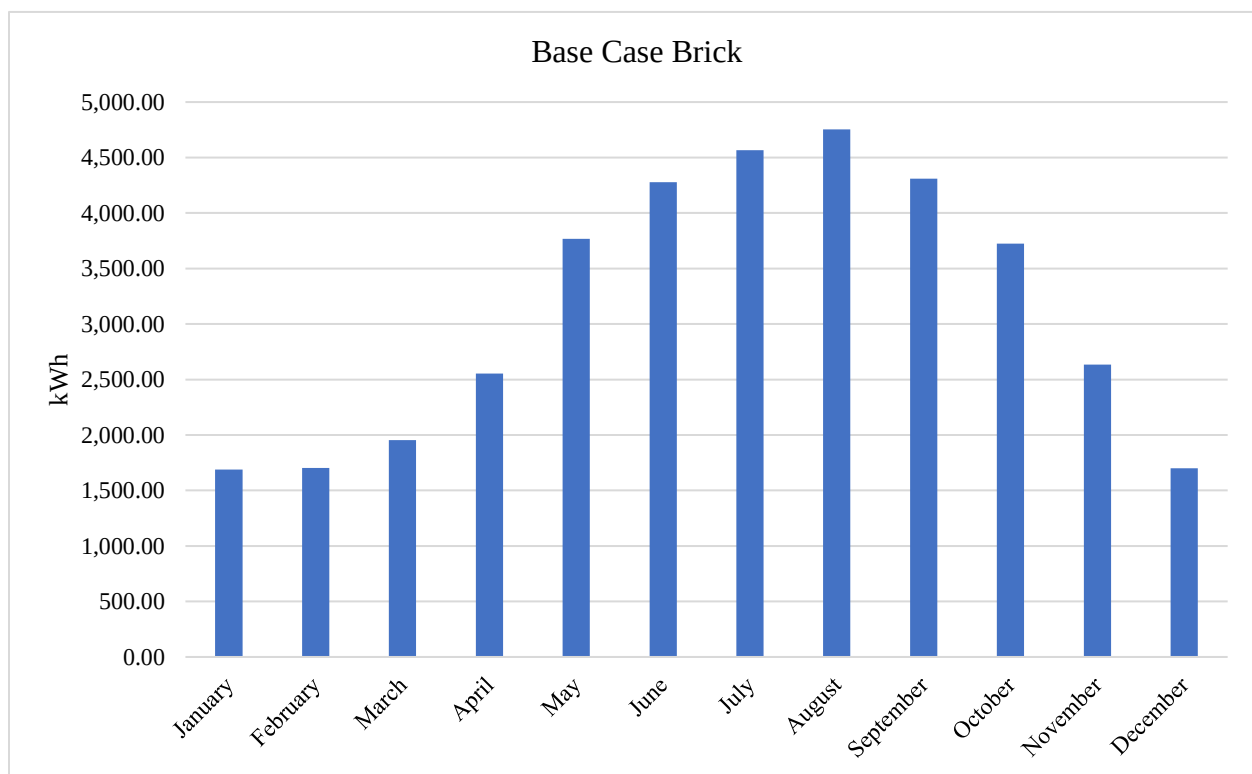


Figure 88. Brick Structure Monthly Energy Pattern.

The difference in pattern in both models comes from the impact of the HVAC performance. The energy breakdown shows that the SIPs model is consuming more energy for cooling in the winter season which seems counterintuitive given the lower outdoor temperatures. SIPs have high thermal resistance, which indicates the demand for cooling may be due to the internal loads (Fig. 89).

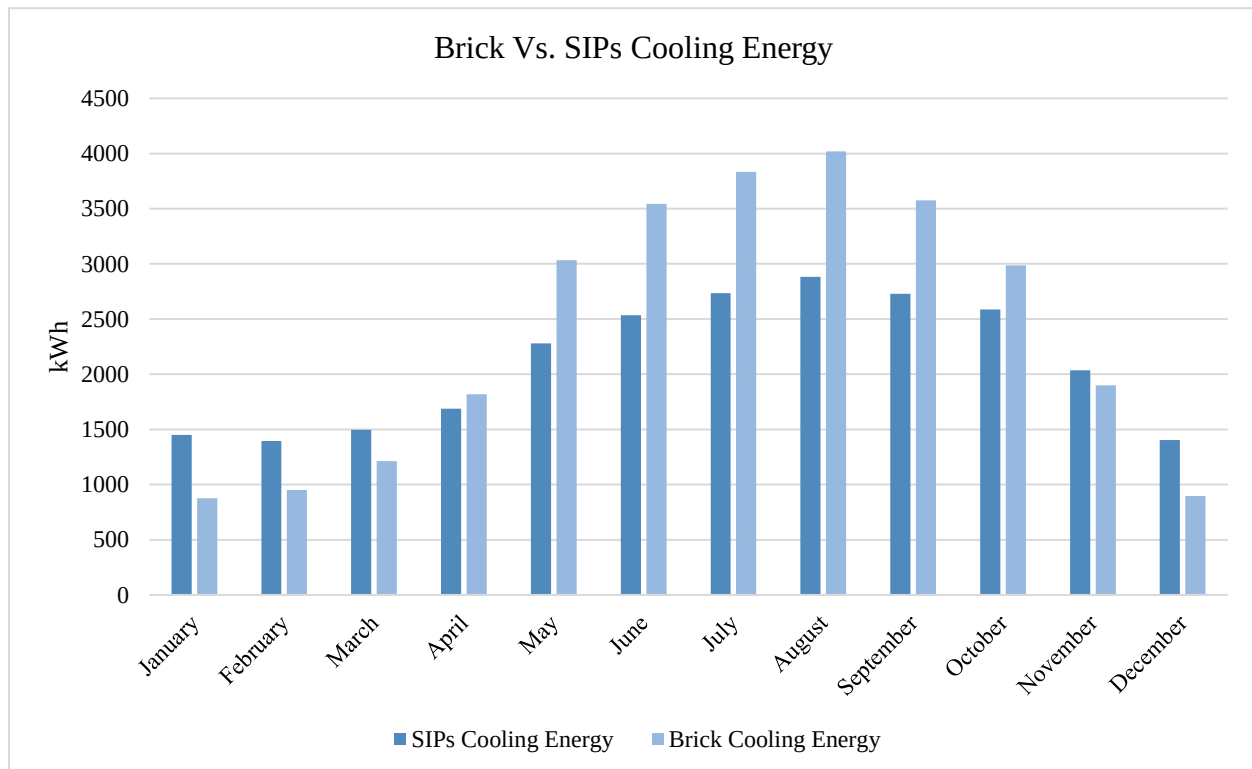


Figure 89. Monthly Energy Pattern Differences.

To prove our assumption about the impact from the internal heat gain that impacts the SIPs cooling energy the base case model was adjusted by excluding all the internal loads to track the difference between the two models' cooling energy. The expectation was for a pattern change in the cooling energy since the heat source was excluded from the model (Fig. 90).

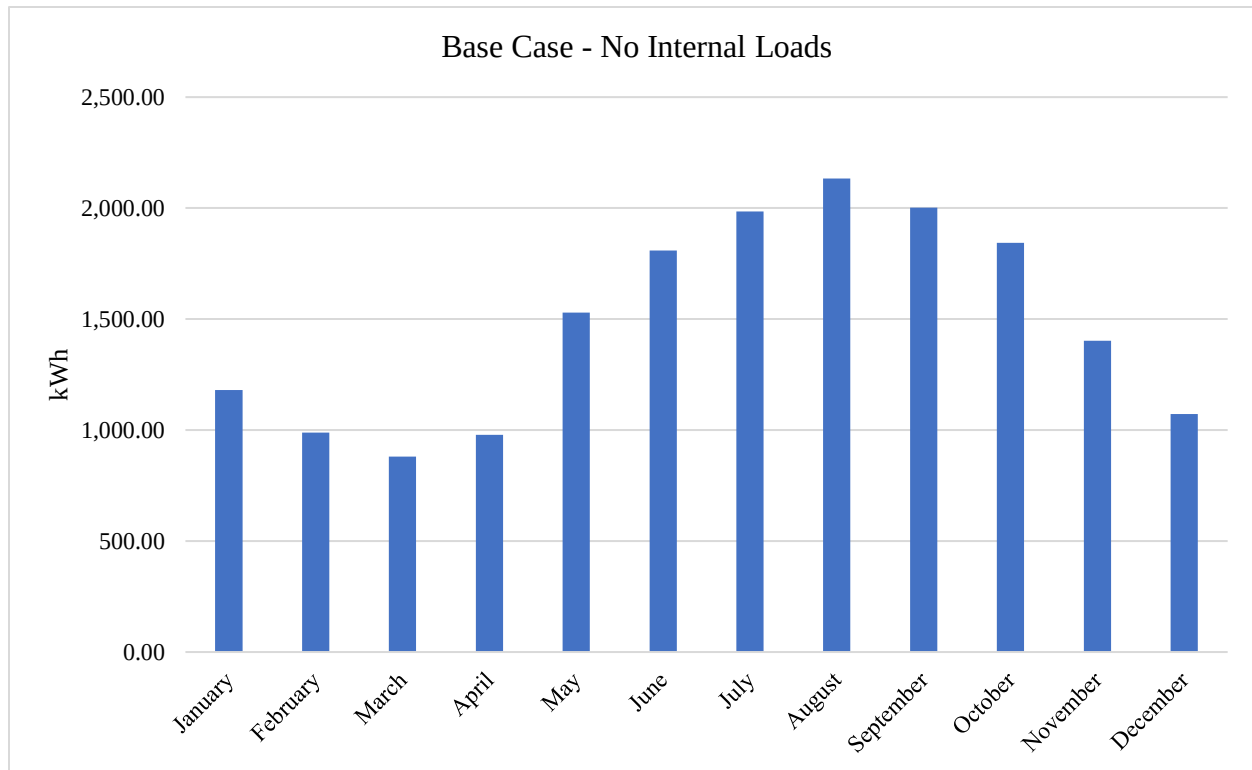


Figure 90. Base case Monthly Energy Pattern.

Unfortunately, the cooling energy is still high even after the exclusion of the internal loads in the base case model. The winter season cooling consumption is still high leading to the conclusion that the internal loads are not the main reason for the pattern change. The breakdown for energy presented by cooling and heating energy still presents an increase in the cooling loads in the winter season starting from December to March (Fig. 91). This suggested the need for further troubleshooting of the model to track the heat source. The last expected source of heat gain in the model was the fenestration; the model has two windows and a glass sliding door as the main entrance. This was investigated and the results were presented in our next section.

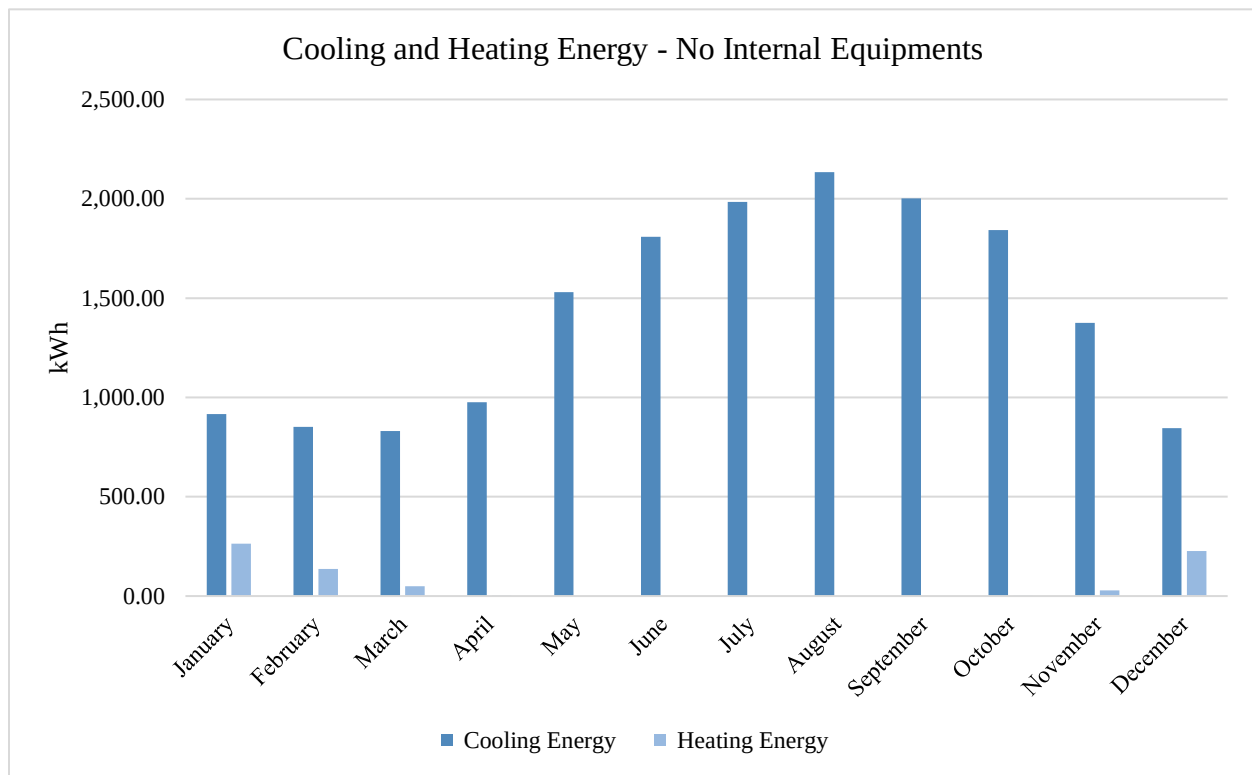


Figure 91. Base Case Model Monthly Energy Pattern After Excluding the Internal Loads.

In this step, the study will investigate the impact of the fenestration and internal loads on the monthly energy pattern and HVAC (cooling and heating) energy in the base case model. The research in this step has excluded the fenestration and internal loads from the model and presented the simulation results after the exclusion as shown in (Fig 92). The expected result is to witness a total reduction in the cooling loads to a normal level since the heat source is being excluded which will present its impact on the monthly energy pattern and HVAC energy loads breakdown (Fig. 93). The study depends on this step to validate the base case model since it is the last explanation for the cooling energy difference.

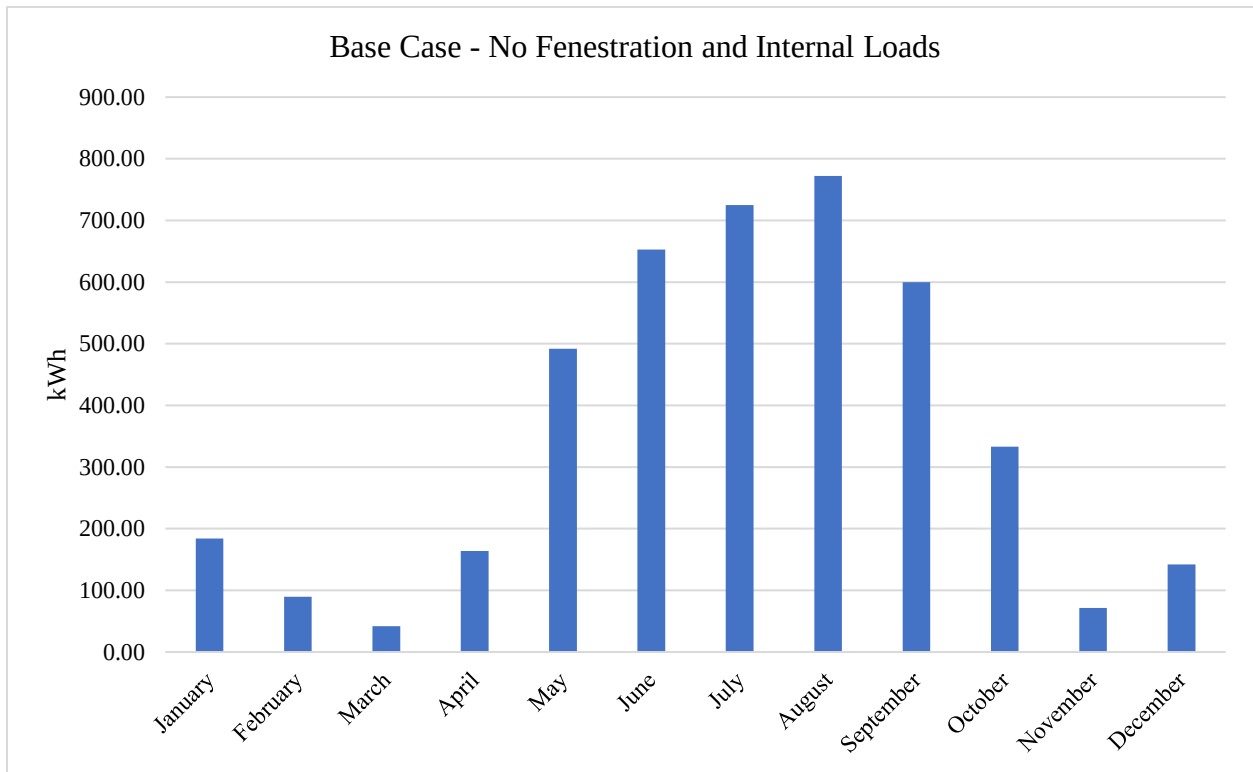


Figure 92. The Overall Monthly Pattern Which Demonstrates the Impact of the Adjustment.

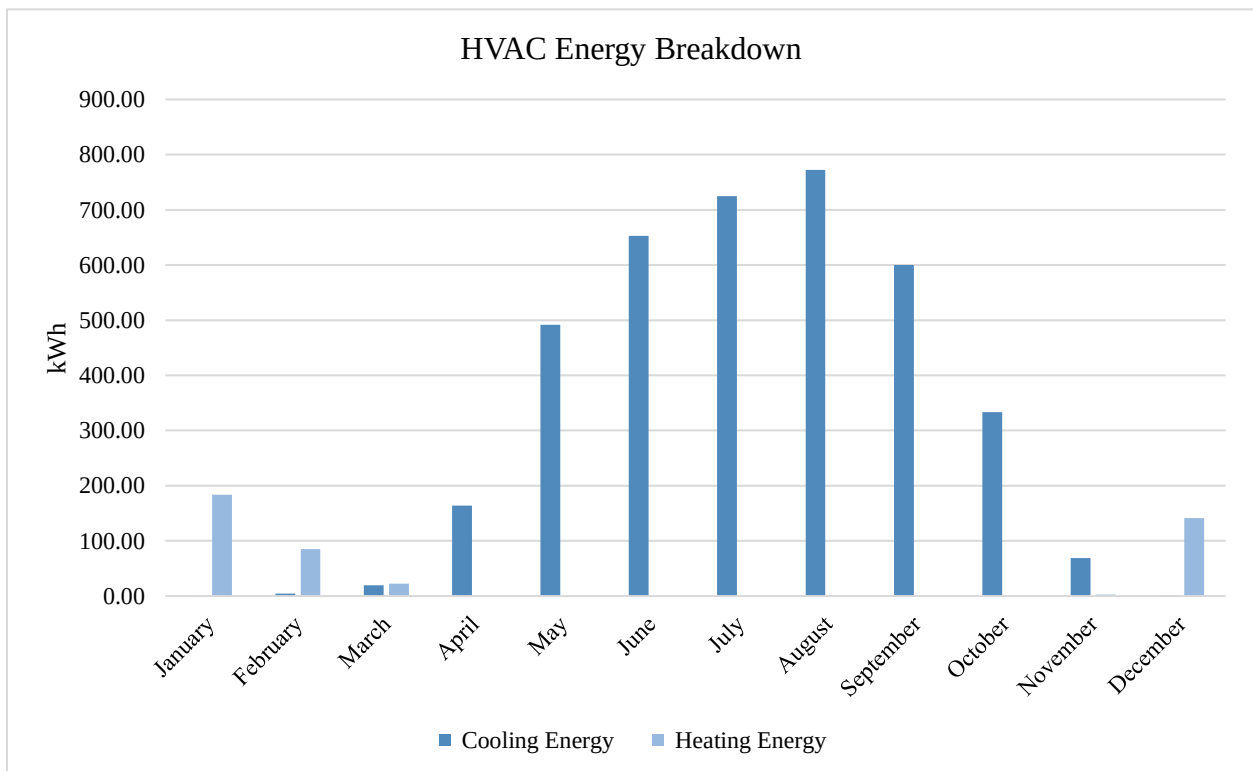


Figure 93. Base Case Cooling and Heating Energy after Excluding Fenestration and Internal Loads.

The simulation results, after excluding both internal loads and fenestration, show a significant reduction in monthly energy consumption, highlighting the substantial impact of these two factors on the simulations (Fig. 92). The unjustified high cooling energy levels during the winter season occurred due to solar heat gain through the model's fenestration and internal loads heat gain. This, in turn, increased the cooling energy required to meet the cooling system setpoint. Removing the fenestration reduced heat gain inside the model and decreased the cooling load energy by 52%.

The last investigation illustrated the critical impact of one model element on the overall energy performance. Therefore, the study added another objective: to investigate each model element individually by applying the exclusion method to elements such as the water heater, fenestration, lighting, and the like to assess their impact and contribution to the model's total energy consumption. The following schedule demonstrates the impact of each element and its proportion of total energy consumption (Table 7).

In conclusion, this section investigated the pattern differences in monthly energy consumption, which were primarily due to the excessive cooling loads in the SIPs model during the winter season. The model was expected to show lower cooling energy demands in winter due to the decrease in outdoor temperature. However, troubleshooting the base case model revealed that the pattern differences were mainly caused by heat gain from internal loads and fenestration, which led to an increased cooling demand. These differences were identified and logically justified, making the model's energy consumption pattern reasonable for the study to proceed to the next section.

Table 7. The Table Demonstrates the Impact of all the Model Elements on the Energy Total if they Excluded.

Model	Total Site Energy [GJ]	Cooling [GJ]	Heating [GJ]	Water Heater [GJ]	Internal Loads Energy [GJ]	Lighting Energy [GJ]
Base Case	124	90	1.7	5.9	24.9	0.9
Energy Portion%		73	1.3	4.7	20	0.7
Base Case - No Lights	122	90	1.7	5.9	24.9	0
Reduction or Increase%	1.3	0.8	2.3	0	0	100
Base Case - No Water Heater	112	84.9	1.7	0	24.9	0.9
Reduction or Increase%	9.4	6.4	1.1	100	0	0
Base Case - No Internal Loads	77.2	68	2.3	5.9	0	0.9
Reduction or Increase%	37.8	25	40	0	100	0
Base Case - No Windows	75.1	42.7	0.6	5.9	24.9	0.9
Reduction or Increase%	39.4	52.8	61.7	0	0	0

5.1.3 Occupancy Schedule Application

When compared to the apartment data the simulation results were expected to show a similar energy consumption pattern since they are about the same size and were for similar climatic conditions (Fig. 83). The apartment has a couple of differences that should be considered when compared to the base case. First, the apartment has a different occupancy schedule for each zone which corresponds to the HVAC operation hours whereas the base case simulation included a continuous dual thermostat setpoint aimed at maintaining the setpoint for the entire space throughout the year. In addition, the bathroom in the apartment was unconditioned.

Other differences between the base case and apartment first included the model having a minimum thermostat setpoint of 18°C for heating and a maximum of 25°C for cooling. Second, the base case had an electric stove, which impacts the energy utilization while adding to the internal heat gains. Therefore, the base case model had to be adjusted to match the apartment schedule while excluding the stove since the apartment utilizes a natural gas stove. Third, the base case has a much larger fenestration area which has a very large impact on the energy results.

To investigate the impact on the results, the occupancy hours input in the base case model were adjusted by setting the HVAC system to be “on” during occupancy hours and “off” when the space is unoccupied. Second, the model was adjusted by changing the bathroom zone from being climate-controlled to non-conditioned as was the apartment. Fourth, the electric stove was set to “off” in the simulation to measure its impact on the overall energy consumption. Fifth, the sliding glass door in the base case was changed to an opaque door. After these adjustments, the simulation results showed a significant reduction in the total site energy. The relative impacts are shown in the following table:

Table 8. Base Case Adjustments Savings.

Adjustment	Total site energy [GJ]	Cooling [GJ]	Heating [GJ]	Water Heater [GJ]	Internal Loads Energy [GJ]	Lighting Energy [GJ]
Base Case	124	90.7	1.7	5.9	24.9	0.9
Occupancy Schedule	71.9	40	0.1	5.9	24.9	0.9
Electric Stove Off	56.3	32.3	0.1	5.9	17	0.9
Fenestration Adjustment	50.1	26.1	0.1	5.9	17	0.9
Total Saving Percentage%	59.6	71.1	94.1	5.9	31.6	0

The impact of changing the occupancy schedule, the bathroom being non-climate-controlled, eliminating the electric stove, and removing the glass from the sliding door reduced the total site energy by 52 GJ. The comparison of the adjusted model with the apartment data is shown in Figure 94.

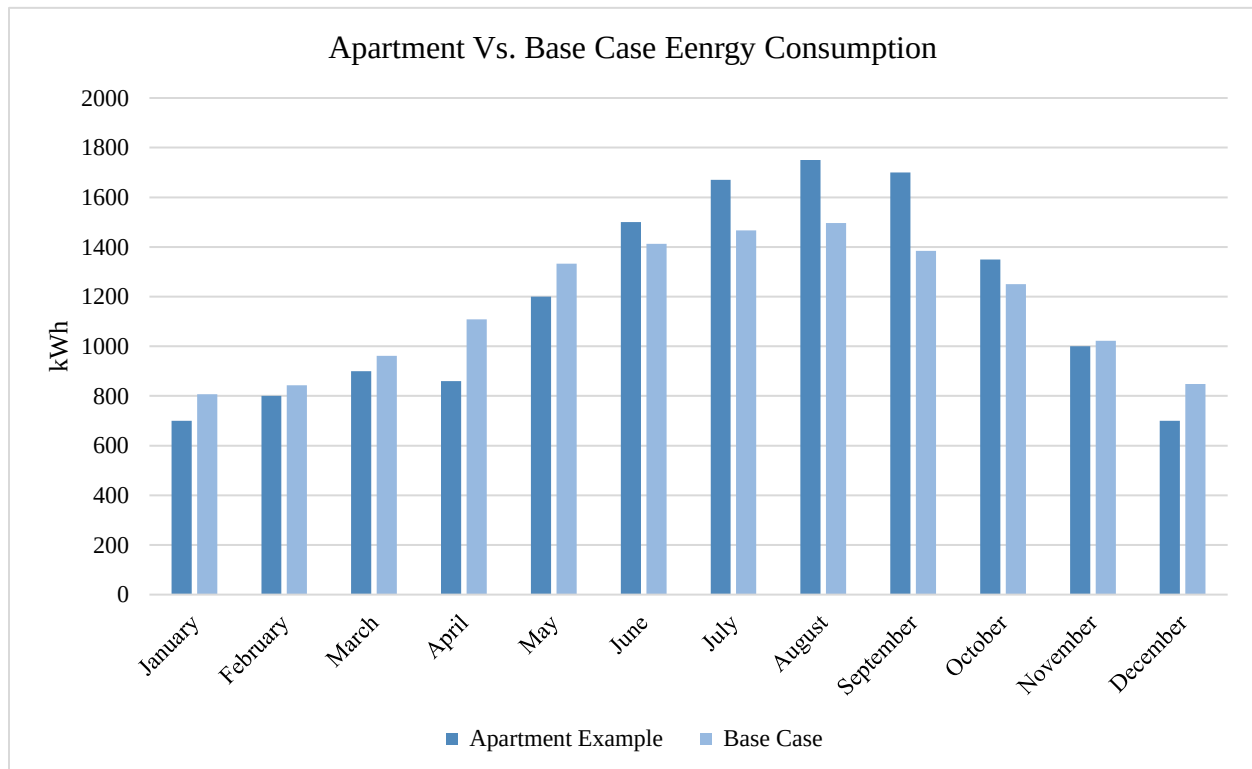


Figure 94. A Visualization of the Base case and Apartment After the Adjustment Application.

The newly calculated EUI for the base case was also significantly reduced from 728 kWh/m²/year (67 kWh/ft²/year) to 293 kWh/m² (27 kWh/ft²/year). As a result of the adjustments, the average difference between the simulations of the base case and the apartment's total site energy decreased from 83% to less than the apartment by 1.3% (Fig. 94). The revised difference between the apartment and the base case provided a more confident degree of validation to the simulation results.

As mentioned, the research aims to examine the application and proper placement and thickness of PCM while maintaining indoor thermal comfort conditions for the entire year. Therefore, it should be noted that the research will utilize the model with the original total site energy of 124 GJ without the adjustments applied to match the apartment example consumption. The base case model was adjusted in the last two sections just to validate the results illustrate the reason for the result differences and ensure that the base case results are valid and can be used for the research in the coming sections.

5.2 Group B and Base Case Model Results

The application of PCM in Group B, with PCM positioned as a second layer from the outside, did not show the expected significant savings compared to the base case—Model A. Overall, the energy consumption within this group remained relatively stable under the influence of PCM, providing only minor reductions in energy consumption across all the models in the group. The energy breakdown showed only a fractional increase in savings for Group B models, with no noticeable improvement as the thickness of the PCM increased as demonstrated in (Fig. 95).

The energy breakdown for this group shows a noticeable impact of PCM application in heating mode, with savings ranging from 11.76% to 15.29%, with the highest thickness in Model B4. Cooling energy reduction was minimal across all models, ranging from 0.31% to 0.62%, also with the highest thickness in Model B4. The application of PCM in this group resulted in a gradual reduction in total site energy, ranging from 0.39% to 0.66% as the thickness increased from Model B1 to Model B4. The following table provides a breakdown of all the savings obtained from the models compared to the base case results (Table 9).

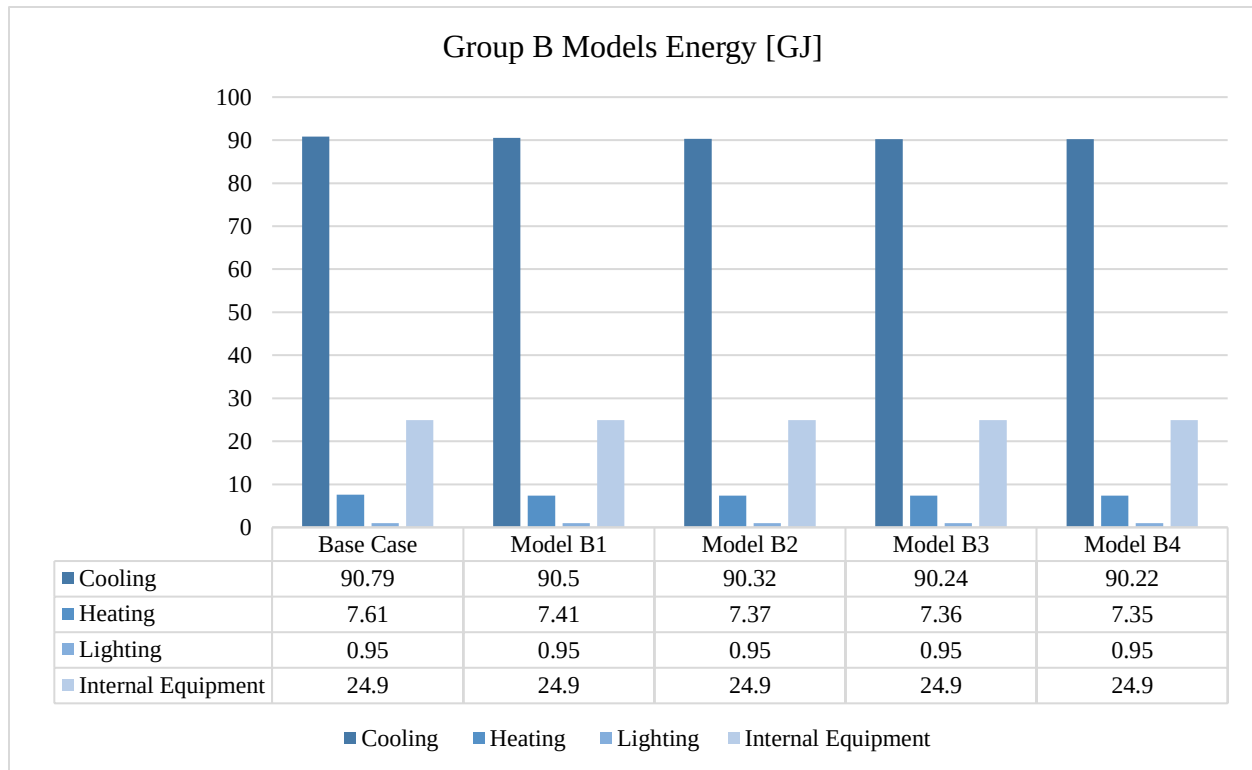


Figure 95. Consumption Results Breakdown for Group B Models under the Impact of PCM as Second Layer from Outside.

Table 8. Percentage Energy Savings Breakdown Across Models Compared to Base Case.

Model	Cooling Saving %	Heating Saving %	Total HVAC Saving %	Total Site Energy Saving %
B1	0.31	11.76	12.07	0.39
B2	0.51	14.11	14.62	0.57
B3	0.6	14.7	15.3	0.64
B4	0.62	15.29	15.91	0.66

In summary, the lowest group observed saving after the application of PCM was observed in Model B1 which had a total site saving of 0.39%. On the other end, the highest saving was achieved in Model B4 by reducing the total site energy and provided a reduction of 0.66% (Fig. 96). Through the observation it's been noticed that as thickness increased, more savings were obtained. Still, the application of PCM from the outside as the second layer didn't achieve high

energy saving as expected making the application in this location within the wall not functional and recommended.

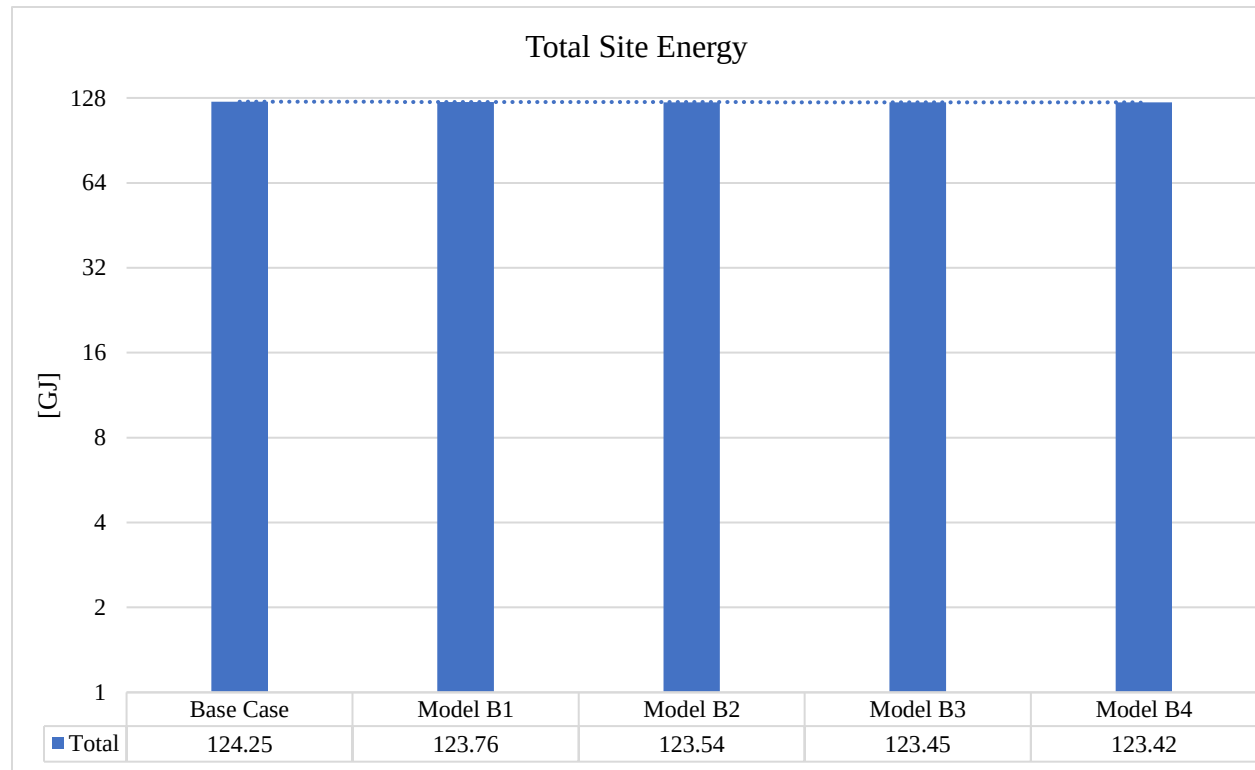


Figure 96. Group B Models - PCM Impact on Total Site Energy.

5.3 Group C and Base Case Model Results

In Group C, PCM was applied as a middle layer within the wall structure by adding XPS foam layers on both sides. Although energy savings presented a better performance in comparison to Group B models it is still not as significant as expected from the application of PCM. The simulation results of monthly energy presented minor changes, in addition to an unexpected pattern of energy reduction and increase from the impact observed in Group B where increased thickness correlated with higher savings (Fig. 97). In this group, the wall structure and PCM position demonstrated a diverse influence on the saving results. The application of PCM started with an

energy saving obtained in Model C1 reversed the saving in Model C2 and started to increase saving again in models C3 and C4 which will be explained thoroughly in the coming section.

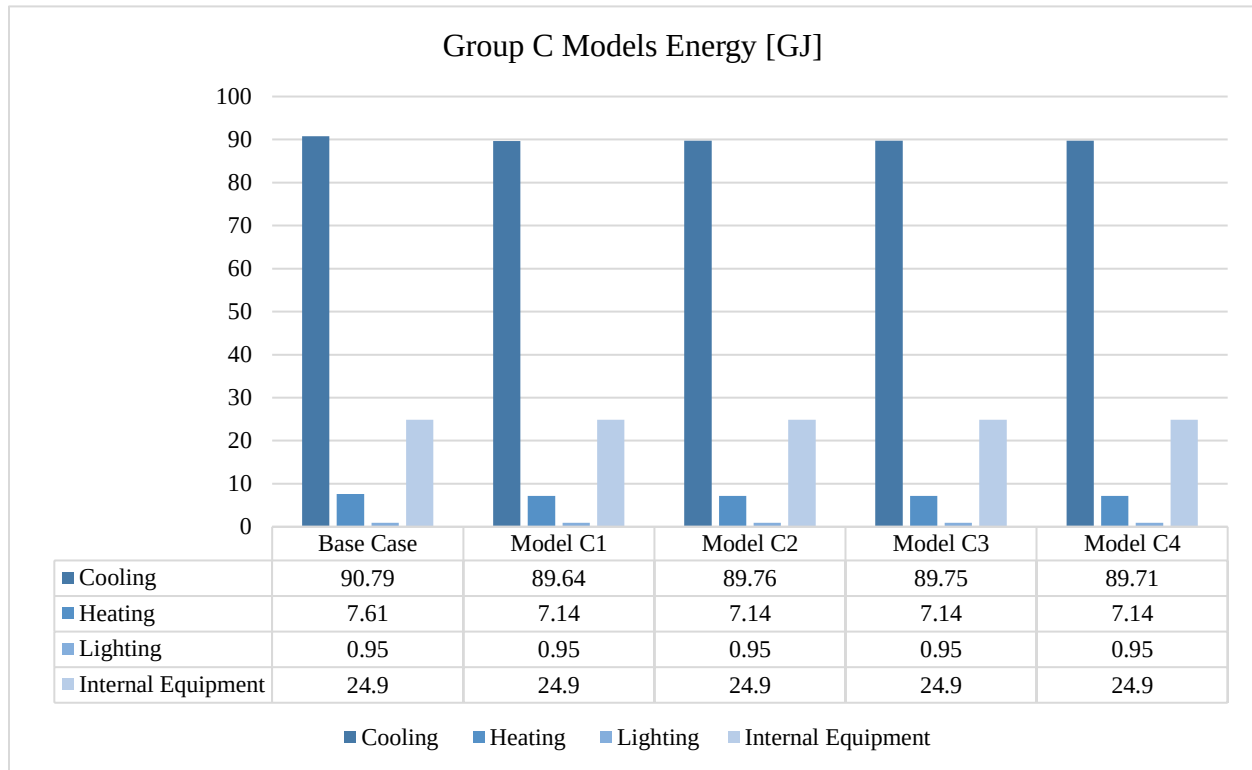


Figure 97. Energy Breakdown for Group C Models under the Impact of PCM as the Middle Layer.

The savings obtained from the application of PCM in this group have shown a better performance by enhancing the total site energy. Model C1 in this group has reduced the base case site energy and provided a saving average of 1.3% as the highest saving percentage obtained in this group with the lowest PCM thickness of 0.5 cm. The other models of C2 and C3 ranged from 1.2 to 1.21% making Model C4 the second model with a higher saving of 1.24%.

To be noted, the wall structure of Group C models presented diverse impacts on performance. Particularly in Model C2 increase in energy consumption reduced the potential energy saving, where PCM thicknesses of 0.1 cm were used. These findings underscore the

significance of carefully determining the appropriate thickness, placement of PCM, and wall layering for optimal performance (Table 10).

Table 9. Percentage Energy Savings Breakdown Across Models Compared to Base Case.

Model	Cooling Saving %	Heating Saving %	Total HVAC Saving %	Total Site Energy Saving Percentage
C1	1.26	6.17	7.43	1.3
C2	1.13	6.17	7.3	1.2
C3	1.14	6.17	7.31	1.21
C4	1.18	6.17	7.35	1.24

The noticeable difference in this group is that the heating saving was reduced and the cooling saving increased when comparing the results between group B and C models. Model C1 gives an overall saving of 1.3% with the lowest PCM thickness of 0.5 cm, this reduction was in both cooling and heating loads, making a 7.4% decrease in HVAC energy. Contrary to expectations, model C2 experienced a reversal in the anticipated reduction trend as thickness increased. When the thickness increased more in Model C3 and C4 started to increase the savings again. In Model C2, the total HVAC saving diminished by 0.1%, driven by a 0.13% reduction in cooling energy. Meanwhile, Model C3 and C4 had a minor increase in cooling energy saving compared to Model C2. The impact in all models in this group came from the cooling energy while the heating energy remained stable.

To conclude, when evaluating the energy-saving potential of PCM applications with varying thicknesses across the entire group. Model C1 has the lowest thickness and this is the most effective in reducing site energy consumption by 1.6 GJ making a saving of 1.3%. While in the second place of energy, reduction is presented by Model C4 with the highest thickness in this group by reducing the total site energy by 1.5 GJ and adding a saving of 1.24% (Fig. 98).

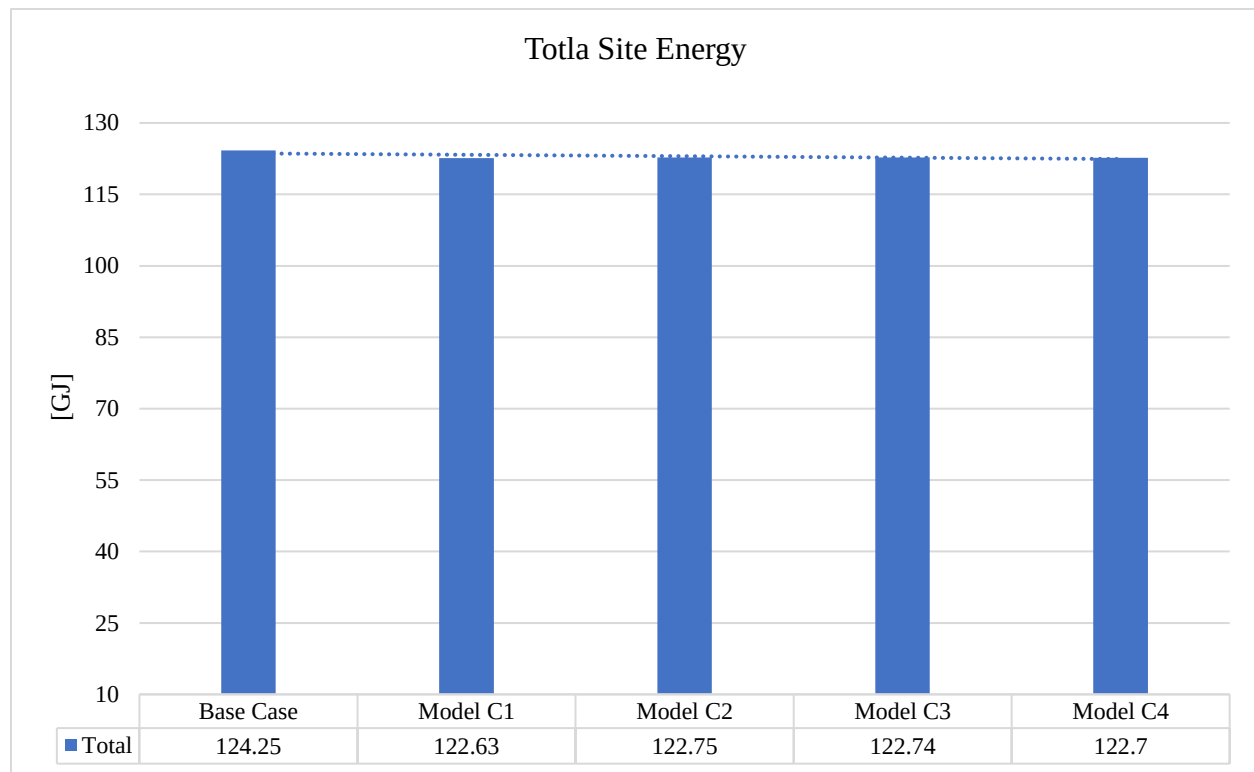


Figure 98. Group C Models - PCM Impact on Total Site Energy.

5.4 Group D and Base Case Model Results

In Group D models, PCM was implemented as the second layer from the inside, successfully achieving the anticipated reduction in energy consumption. The energy savings displayed a remarkable decrease in energy consumption when compared to the previous group models. The correlation between thickness and energy saving was observed in the group performance from the savings obtained. The savings with a remarkable high percentage in Model D1 and the percentage increased gradually in the other models reaching the highest saving in Model D4 with the highest PCM thickness (Fig. 99).

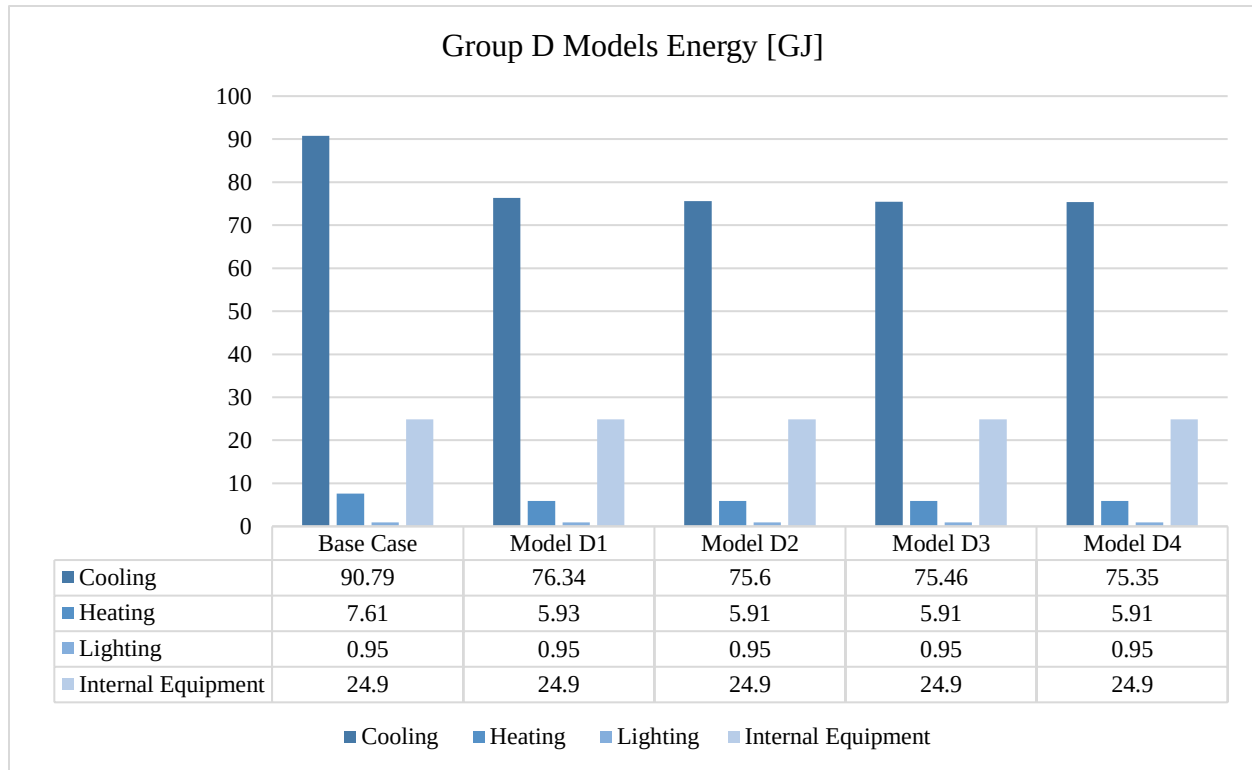


Figure 99. Consumption Results Breakdown for Group B Models under the Impact of PCM as Second Layer from Inside.

Model D1 in this group has reduced the base case site energy greatly and provides a saving average of 12.98% as the lowest saving percentage obtained in this group with the lowest PCM thickness of 0.5 cm. Starting from that point the percentage gained in Model D1 started to increase with the thickness increase reaching 13.2% in Model D2 to the highest percentage of 13.79% in Model D4.

The application of PCM showed its impact in both cooling and heating in this group by resulting in a substantial HVAC load saving of 37.98% with a total saving in site energy of 12.98% in Model D1. The increase in saving percentage in the other models wasn't significant but was decreasing gradually as occurred in the former groups B and C. In Model D4 with the highest thickness in this group, where the total site energy savings reached 13.79%, with HVAC consumption reduction contributing to a total energy saving of 39.33%. The variant in the other

models occurred gradually in the cooling energy, meanwhile, the heating energy remained stable at the same rate from model D3 until model D4 (Table 11).

Table 10. Percentage Energy Savings Breakdown Across Models Compared to Base Case.

Model	Cooling Saving %	Heating Saving %	Total HVAC Saving %	Total Site Energy Saving Percentage
D1	15.9	22	37.98	12.98
D2	16.7	22.33	39	13.2
D3	16.88	22.33	39.2	13.7
D4	17	22.33	39.33	13.79

The impact of applying PCM in this group was particularly significant since the thickness increase demonstrated both enhancing and reducing effects on energy savings. The optimal thickness led to the highest energy savings identified in Model D4. The model achieved a total site energy saving of 13.79% by reducing the consumption from 124 GJ to 107 GJ. Model D2 and D3 performed similarly and a difference occurred in the cooling energy. The increase in thickness has made a fraction increase in the cooling energy range from 16.7 to 16.88%. Even though the highest energy reduction that contributed to the highest energy saving was obtained in model D4, the significant reduction starting point was in model D1 with the highest drop in the total site energy by 16 GJ demonstrating the benefits of PCM application for energy saving (Fig. 100).

The application of PCM was investigated in this chapter by comparing simulation results that involved adding PCM to the wall structure in different placements and thicknesses across

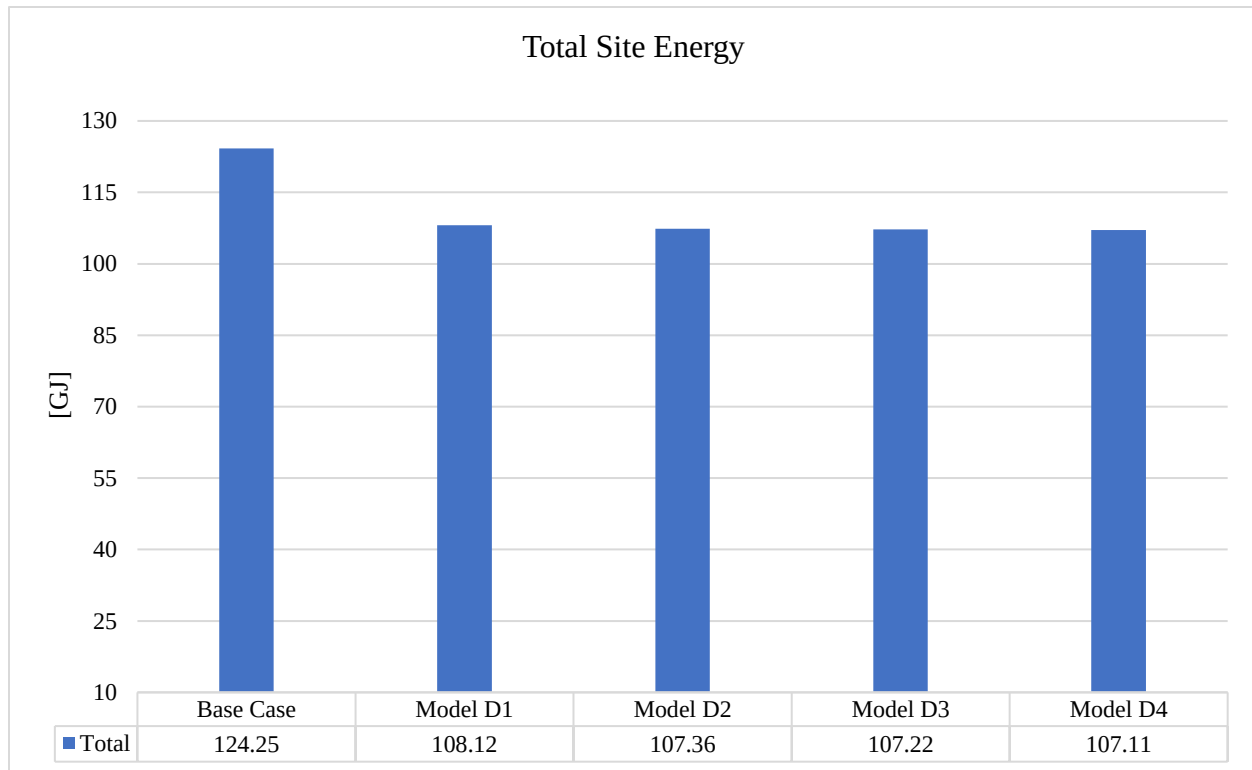


Figure 100. Group B Models - PCM Impact on Total Site Energy.

designated Groups B, C, and D models. These were then compared to the base case Model A, which had no PCM. The simulation results were analyzed and discussed to identify the optimum model within each group. According to their performance under the impact of PCM application and total energy savings, the optimum models were determined as follows: Model B4 in Group B, C1 in Group C, and Model D4 in Group D. The total site energy savings obtained from Group B and C were minor and didn't appear to be attractive for PCM application. In contrast, when Models group D saving was obtained which made PCM application benefits appear on the energy consumption and the thermal performance. (Fig. 101).

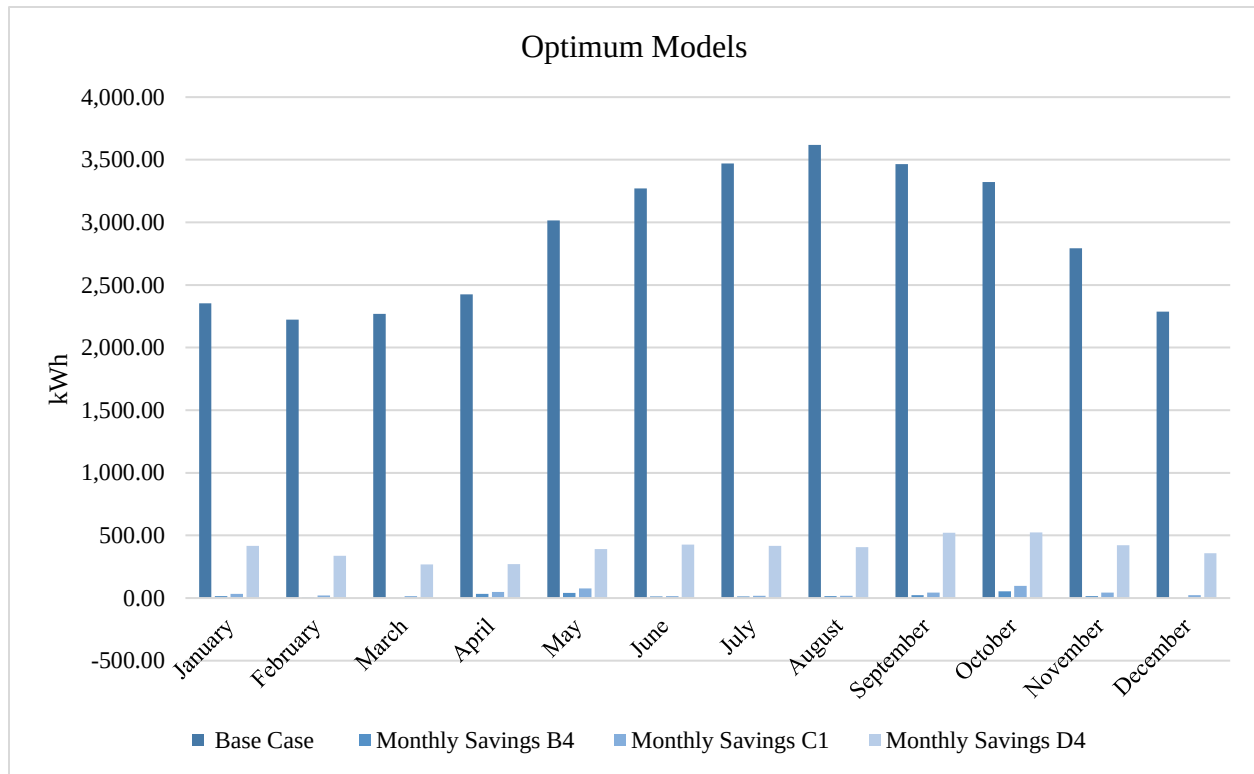


Figure 101. The optimum Models Savings Obtained from PCM Application.

In group B, the simulation results demonstrated an increase in savings correlated with the thickness increase. Model B4 with the highest thickness of PCM 0.2cm was the optimum in this group by providing a total site energy saving of 0.6%. In group C, in general, the group result has performed better than group B. The simulation has shown unexpected energy patterns under the impact of PCM. The increase in thickness is expected to increase energy saving. Model C2 has reversed the savings by reducing the savings gained in Model C1. The energy saving was recovered gradually in models C3 and C4 when using 1.5 and 2.0 cm thickness but still didn't provide a saving better than C1. However, Model C1 with the lowest thickness of 0.5 cm was the optimum for saving energy by making a saving in the total site energy of 1.3%. In group D, the application of PCM was significant which could be seen through the monthly saving variation. The adding

thickness has shown a continuous saving increase correlated with the increase of PCM thickness making model D4 the optimum model in this group by providing a site energy saving of 13.7%.

5.5 Sensitivity Analysis

An investigation of two-way sensitivity analysis on model D were applied to test the simulation model's sensitivity. This technique assesses the strength of a model-based analysis by simultaneously changing the values of two key input variables. The PCM thickness variable has been varied by tenths between low and high, while maintaining the baseline as (Baseline: 0.005, Low: 0.0045, High: 0.0055). The results indicated that the low variation input caused a difference of 0.2% from the baseline, while the high variation input caused a 0.1% difference. These slight variations do not significantly affect the model and prove its reliability (Fig. 102). The second variable analyzed was the material thermal conductivity. The study applied an increase of 5% for the high value (1.1445 W/m·K) and a decrease of 5% for the low value (1.0355 W/m·K). These changes have resulted in a 0.0% difference for both the increase and reduction in thermal conductivity input, further proving the simulated model's reliability (Fig. 103). The sensitivity analysis could include a broader range of variables, providing a clear understanding of the factors influencing the thermal performance of SIPs integrated with PCM. The focus on PCM thickness and thermal conductivity were particularly important for this study to be aligned with the research goals.

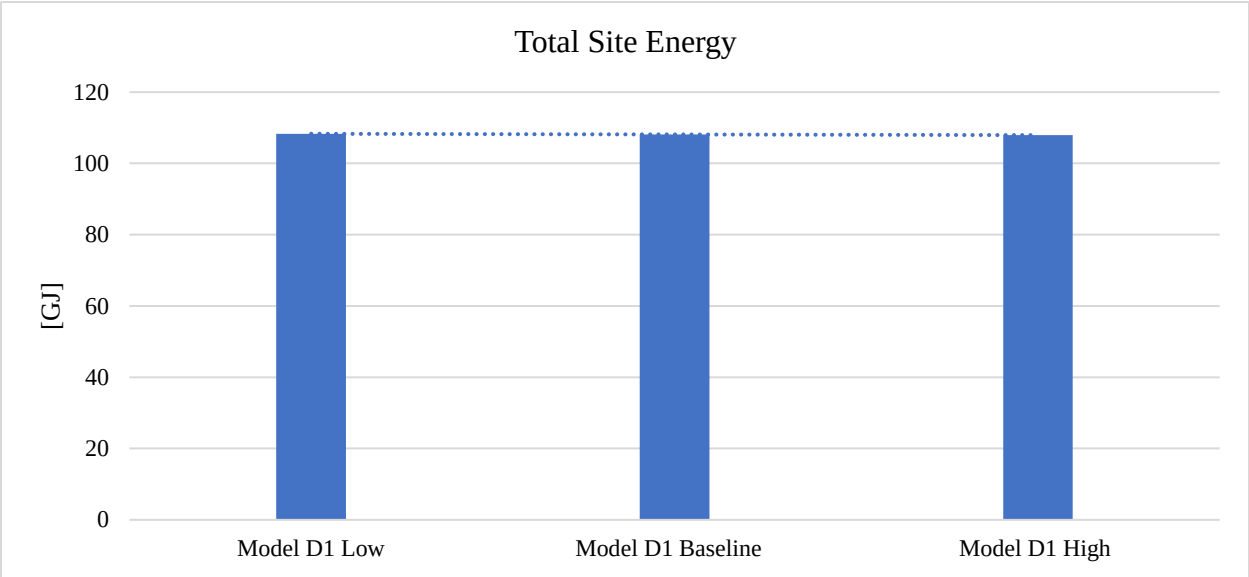


Figure 103. Sensitivity Analysis on PCM Thickness Variable Variation Results.

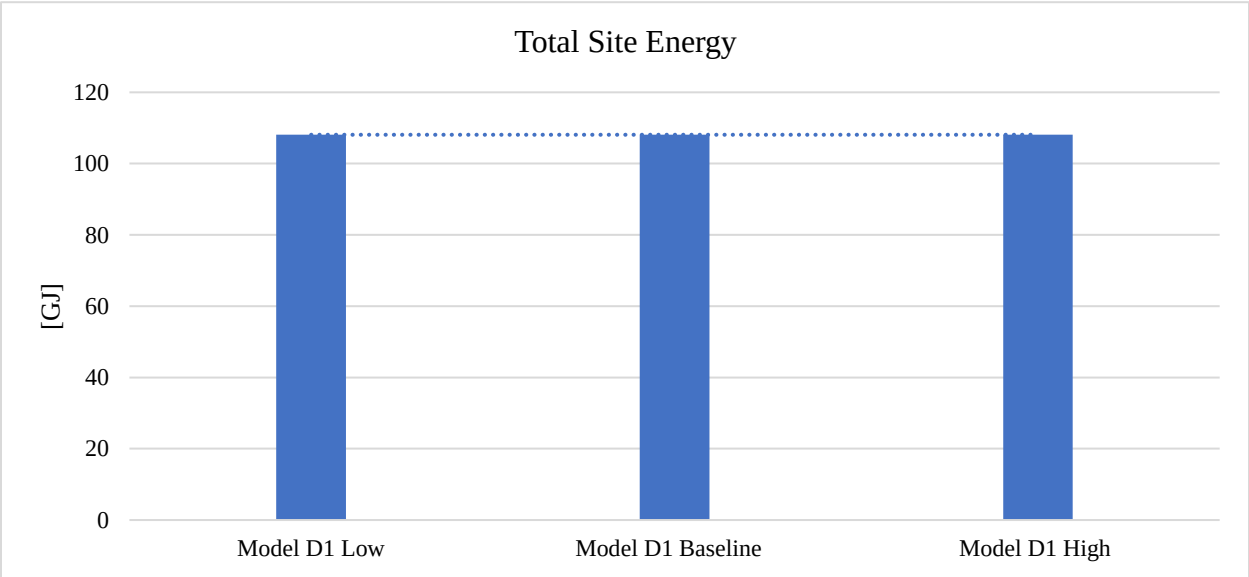


Figure 102. Sensitivity Analysis on PCM Thermal Conductivity Variable Variation Results.

Chapter 6: LCCA Analysis

In this chapter, the study explored the application of PCM as an investment by conducting an LCCA analysis. This analysis was based on the optimal model as identified in Chapter 5. To conduct the LCCA, the following factors were obtained: the initial cost of PCM, energy-saving averages, and the electricity rate. Two of the required inputs, including energy savings and electricity rates, were obtained from previous chapters. Calculating the initial cost of PCM involves considering the panel sizing, project size per square foot for panel count, the cost of purchasing the panels, installation costs, and the cost of adding PCM to the panels. In the upcoming section, the pricing of the panels was used to compute the cost of panels needed for the project. Additionally, the installation costs were determined to then establish the base case cost with and without PCM.

6.1 PCM Initial Cost

The process of determining the initial cost went through four phases. First, we start with the panel pricing to identify the price of the panels used and determine the required number of panels associated with the purchase costs. The second phase involved estimating the installation cost for the entire project by examining labor costs and the time required to complete the installation. In phase three, the quantity of PCM needed for the project was calculated. This involved reaching out to suppliers for quotes to obtain an estimation of the PCM material costs. In the fourth phase, we determined the cost of installing PCM in the SIPs from suppliers and manufacturers. This comprehensive approach allowed the final cost of the base case with the application of PCM to be determined.

1/ Panels Pricing

- The panel size utilized was 4×12 ft with a thickness of 8.25” (1.2×3.6 m thickness 20 cm).
- According to the ACMEPANEL website (SIPs Pricing, 2024), the panel price per ft² is \$9.7
- The panel size is 48 ft² (4.4 m²).
- Panel count calculation:
 - Base case exterior wall area = (Length × Width × Height).
 - $(24 \times 3.5) + (7.9 \times 3.5) = 1201 \text{ ft}^2 / (111 \text{ m}^2)$.
 - Roof and Floor = Length × Width.
 - $12 \times 3.95 \times 2 = 1020 \text{ ft}^2 / (94.8 \text{ m}^2)$.
 - Subtracting window area from the total:
 - Window total area = 40 ft² / (3.7 m²).
 - Total without window area = 2182 ft² / (202 m²).
 - Panel count = Total envelope area / panel area.
 - $2182.16 \text{ ft}^2 / 48 \text{ ft}^2 = 46 \text{ panels}$.
- Base case SIPs Purchase Cost = Total envelope area × panel price per ft².
 - Cost = $2182 \text{ ft}^2 \times \$ 9.7 = \$21,232$.

2/ Installation Cost Estimation:

- According to the INNOVA PANEL website (SIP Building Kit Cost, 2024) for similar projects:
- A construction crew of 5 people / The average for panel installation is about 20 Minutes per panel – The cost hour per person for the installation is \$45 an hour, \$225 for tools – with the consideration of 120 mph wind rating during the installation.

- Installation period = Panels count $\times$ Installation time.
 - $46 \times 20 = 909$ minutes (about 15.15 hours) and add 30% for first-time installing SIPs.
 - $15.15 + 4.5 = 19.6$ Hours.
 - On an 8-hour work shift, the Villa assembly will take about 2.5 days.
- Installation Cost = Installation period $\times$ Crew hourly rate.
 - $= 19.6 \times 225 = \$4,410$.
- Total cost of Building = SIPs Cost + Installation Cost.
 - Total cost of Building = $21,232 + 4,410 = \$25,642$.

3/ PCM Purchase Pricing:

- According to INSOLCORP (2022), the PCM price is \$4.85 per sq. ft., covering 24 sq. ft. per carton (6 tiles).
- The cost of PCM for the base case should be calculated as follows:
 - Cost of PCM = Wall area without roof and floor $\times$ Price per sq. ft.
 - Cost of PCM = $1,161 \text{ ft}^2 \times \$ 4.85 = \$5,635$ for a 0.5 cm PCM layer.

4/ PCM Installation Cost:

According to local home builders (Espinosa Construction, 2023) and SIPs suppliers, the average cost for installing PCM to the panels is as follows:

- For outer or inner placement, the cost is approximately \$1.2 to \$1.9 per square foot, averaging \$1.5
- Placing PCM in the middle of the panels incurs a cost of about \$3.0 to \$3.5 per square foot, with an average of \$3.2

A single layer of 0.5 cm PCM costs around \$5,634 for the material plus \$1.5 for PCM installation per square foot. The calculation for the cost of Model B1 is as follows:

- Cost of Model B1 = Total cost of Building + Cost of PCM + (Wall area with PCM $\times$ 0.8).
 - Substituting the values:
 - Cost of Model B1= $25,642 + 5,634 + (1,161 \times 1.5) = \$33,076$
 - So, the cost of Model B1 is \$33,076.

After calculating the purchase and installation costs of the SIPs, the estimated cost of constructing the base case envelope without the foundation cost and PCM is approximately \$25,642. It is important to note that the cost of the models may vary based on the applied thickness. Considering the PCM material cost estimation, the application of a single layer of PCM with a thickness of 0.5 cm, using the median average cost for installation of \$1.5 for outside layer utilization, will start at approximately \$33,076 as the initial cost with the lowest PCM thickness. In summary, all the necessary factors for the LCCA model have been collected. However, the analysis must account for future uncertainties, and the approach to addressing these uncertainties will be explained in the following section.

6.2 Accounting for Uncertainties Over Time

In this phase, the researcher sought to address the impact of inflation on the initial cost of PCM by utilizing the US Inflation Rates spanning from 2010 to 2023 (Current US Inflation Rates, 2024). From this data, a median average annual increase of 2.87% was established. This inflation rate estimate was then used to calculate future prices and to perform a price forecast for the initial cost. The assumed average rate is a crucial factor in our study since it is applied annually in our LCCA model for material supply and production costs.

To establish KSA electricity rate factor, the first thought was to utilize historical data for electricity rates. However, there are no available historical records for this except for the one documented by Mohammad Aldubyan in 2021, revealing a substantial rise of 260% in electricity

rates during the year 2018. Due to the fact no clear annual history of electricity rate data is currently available in KSA, the researcher has adopted the US electric rate inflation history. According to the U.S. Energy Information Administration (EIA), electricity rates have increased by 2.67% per year in the United States for the past 25 years. Based on inflation rate data obtained, the average will be applied to the annual electricity rates in the LCCA models.

This section has described the phase of work that aimed to adopt a comprehensive and well-informed approach to a developed cost model, aligning this model with real-world trends in inflation and electricity rates. This approach was implemented to improve the reliability of cost projections. It functions as a proactive measure to ensure the accuracy and reliability of cost estimations, taking into account unforeseen challenges associated with inflation in construction projects.

6.3 LCCA Analysis on Optimum PCM Model

In this section, the LCCA results are presented. As previously mentioned, the initial cost of PCM was calculated based on the cost of purchasing the material and the installation cost. The variable's results were collected and calculated in an Excel sheet and the results representation was discussed and presented in the process. The aim is to apply the analysis of the LCCA on all the optimum models that have achieved savings from each group to demonstrate the important benefits between thickness and saving and the PCM placement impact within the envelope. Due to the weak performance and saving from other group models compared to Group D models, the study conducted the LCCA on the models that obtained the highest significant energy saving, which were models D1 and D4 from Group D. The two models have the highest energy savings and with a different thickness, which illustrated and fulfilled the aim of the study to proceed.

6.4 LCCA Analysis

The analysis started with models D1 and D4 with typical scenarios, applied the inflation and electrical rate increase in coming sections, and utilized the information collected from former chapters in the LCCA model structure (Table 12).

Table 12. Optimum Models Cost Estimation: LCCA Inputs.

Model	Model Construction Cost	PCM cost	PCM Installation Cost	PCM Total cost	Model Total Cost	Total Saving
Model D1	\$25,642	\$5,635	\$1800	\$7,435	\$33,077	12.98%
Model D4	\$25,642	\$22,543	\$7,200	\$29,743	\$55,385	13.79%

The initial cost is not excessive in model D1 due to the use of only one layer of PCM under the assumed average electricity rate and maintaining other fixed variables. The application of PCM achieved an average annual saving of 12.98%, which will be recovered within 10 years as the study aims and subsequently generated passive savings of \$15K over the next 20 years (Fig. 104 & 105).

	A	B	C	D	E	F
	Year	Total site energy kWh	PCM Initial cost in US currency	Saving average 12.98% in kWh	Saving per year in dollars	Cumulative annual saving in dollars
1	1	34,511.11	7435.92	4,479.54	747.19	747.19
2	2	34,511.11	7435.92	4,479.54	747.19	1494.38
3	3	34,511.11	7435.92	4,479.54	747.19	2241.56
4	4	34,511.11	7435.92	4,479.54	747.19	2988.75
5	5	34,511.11	7435.92	4,479.54	747.19	3735.94
6	6	34,511.11	7435.92	4,479.54	747.19	4483.13
7	7	34,511.11	7435.92	4,479.54	747.19	5230.31
8	8	34,511.11	7435.92	4,479.54	747.19	5977.50
9	9	34,511.11	7435.92	4,479.54	747.19	6724.69
10	10	34,511.11	7435.92	4,479.54	747.19	7471.88
11	11	34,511.11	7435.92	4,479.54	747.19	8219.06
12	12	34,511.11	7435.92	4,479.54	747.19	8966.25
13	13	34,511.11	7435.92	4,479.54	747.19	9713.44
14	14	34,511.11	7435.92	4,479.54	747.19	10460.63
15	15	34,511.11	7435.92	4,479.54	747.19	11207.81
16	16	34,511.11	7435.92	4,479.54	747.19	11955.00
17	17	34,511.11	7435.92	4,479.54	747.19	12702.19
18	18	34,511.11	7435.92	4,479.54	747.19	13449.38
19	19	34,511.11	7435.92	4,479.54	747.19	14196.57
20	20	34,511.11	7435.92	4,479.54	747.19	14943.75
21	21	34,511.11	7435.92	4,479.54	747.19	15690.94
22	22	34,511.11	7435.92	4,479.54	747.19	16438.13
23	23	34,511.11	7435.92	4,479.54	747.19	17185.32
24	24	34,511.11	7435.92	4,479.54	747.19	17932.50
25	25	34,511.11	7435.92	4,479.54	747.19	18679.69
26	26	34,511.11	7435.92	4,479.54	747.19	19426.88
27	27	34,511.11	7435.92	4,479.54	747.19	20174.07
28	28	34,511.11	7435.92	4,479.54	747.19	20921.25
29	29	34,511.11	7435.92	4,479.54	747.19	21668.44
30	30	34,511.11	7435.92	4,479.54	747.19	22415.63

Figure 104. LCCA Model Screen Shot.

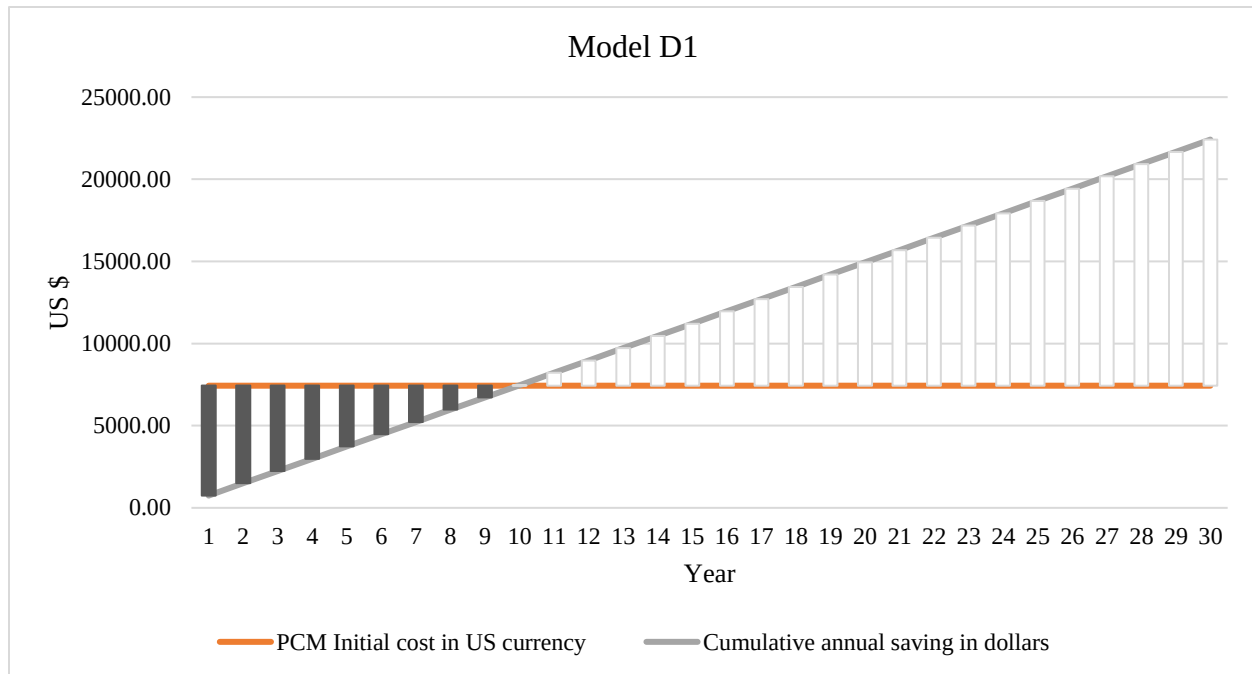


Figure 105. Model D1 LCCA Analysis Normal Scenario.

The LCCA model uses the dollar currency and US electrical rate; the cost of the PCM needs to be converted to Saudi Riyals (SAR) and applied to the LCCA model besides the domestic KSA electrical rate. Therefore, a model titled D1/KSA was established to apply these measurements. This conversion is necessary to determine the years required for investment return if the cost were in Riyals to apply to KSA (Fig. 106).

The LCCA analysis of the D1/KSA Model after the application of the previous measures has shown that PCM material would be unfavorable since it does not meet the investment expectations of the initial cost of PCM to be returned as annual passive savings within the time frame of 8 – 10 years. However, the cost of PCM material in Riyals is excessive, even with the improved performance obtained compared to the low electricity rate in KSA. The LCCA analysis demonstrated that the return on the initial cost of PCM will not be collected even after 30 years (Fig. 107). The period for investment return is cost prohibitive it and will be unappealing to implement the application of PCM in KSA unless a price adjustment is proposed.

	A	B	C	D	E	F
1	Year	Total site energy kWh	PCM Initial cost in KSA currency	Saving average 12.98% in kWh	Saving per year in Riyals	Cumulative annual saving in Riyals
2	1	34,511.11	27884.70	4,479.54	806.32	806.32
3	2	34,511.11	27884.70	4,479.54	806.32	1612.64
4	3	34,511.11	27884.70	4,479.54	806.32	2418.95
5	4	34,511.11	27884.70	4,479.54	806.32	3225.27
6	5	34,511.11	27884.70	4,479.54	806.32	4031.59
7	6	34,511.11	27884.70	4,479.54	806.32	4837.91
8	7	34,511.11	27884.70	4,479.54	806.32	5644.22
9	8	34,511.11	27884.70	4,479.54	806.32	6450.54
10	9	34,511.11	27884.70	4,479.54	806.32	7256.86
11	10	34,511.11	27884.70	4,479.54	806.32	8063.18
12	11	34,511.11	27884.70	4,479.54	806.32	8869.49
13	12	34,511.11	27884.70	4,479.54	806.32	9675.81
14	13	34,511.11	27884.70	4,479.54	806.32	10482.13
15	14	34,511.11	27884.70	4,479.54	806.32	11288.45
16	15	34,511.11	27884.70	4,479.54	806.32	12094.76
17	16	34,511.11	27884.70	4,479.54	806.32	12901.08
18	17	34,511.11	27884.70	4,479.54	806.32	13707.40
19	18	34,511.11	27884.70	4,479.54	806.32	14513.72
20	19	34,511.11	27884.70	4,479.54	806.32	15320.03
21	20	34,511.11	27884.70	4,479.54	806.32	16126.35
22	21	34,511.11	27884.70	4,479.54	806.32	16932.67
23	22	34,511.11	27884.70	4,479.54	806.32	17738.99
24	23	34,511.11	27884.70	4,479.54	806.32	18545.30
25	24	34,511.11	27884.70	4,479.54	806.32	19351.62
26	25	34,511.11	27884.70	4,479.54	806.32	20157.94
27	26	34,511.11	27884.70	4,479.54	806.32	20964.26
28	27	34,511.11	27884.70	4,479.54	806.32	21770.58
29	28	34,511.11	27884.70	4,479.54	806.32	22576.89
30	29	34,511.11	27884.70	4,479.54	806.32	23383.21
31	30	34,511.11	27884.70	4,479.54	806.32	24189.53

Figure 106. Model D1/KSA' LCCA Analysis.

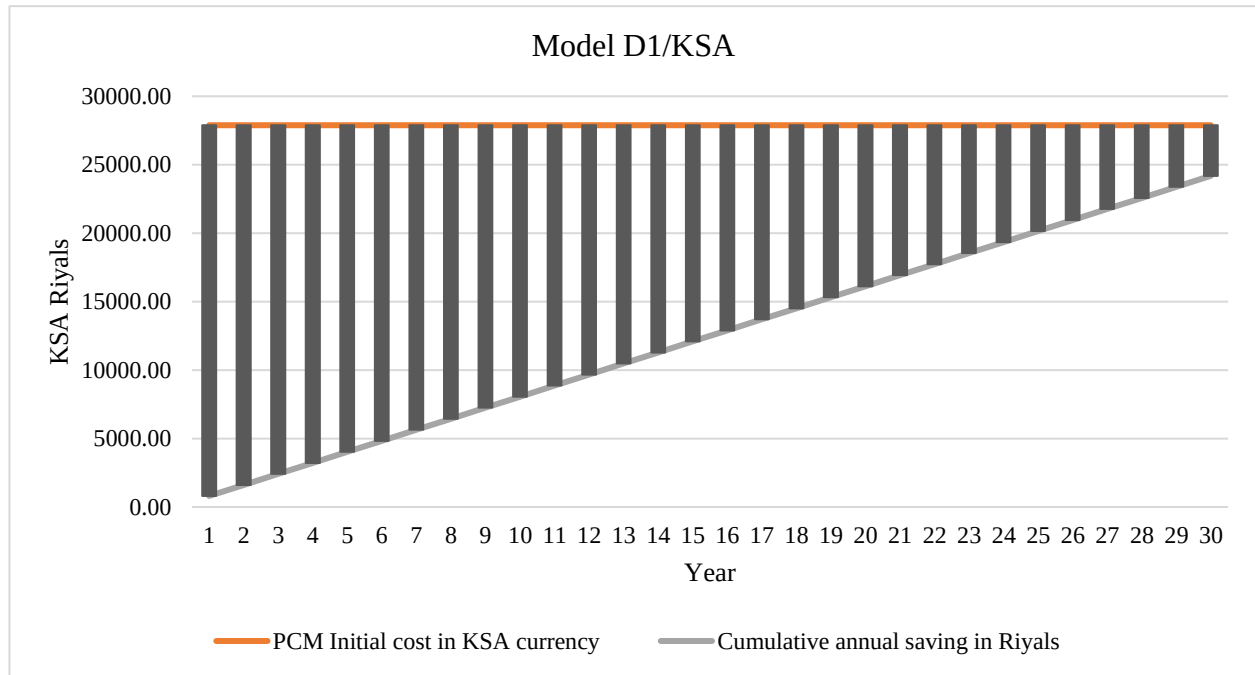


Figure 107. LCCA Model: Initial Cost of Model D1/KSA Vs Cumulative annual saving.

6.4.1 Price Adjustment

For the application of PCM to be appealing, it has to return the initial cost of no more than 8-10 years. To calculate the price for the initial cost to be recovered, the LCCA analysis used the cumulative annual passive saving to determine the proper initial cost. Based on the LCCA data in the 8th and 10th year return plans, the initial cost of PCM must be ranged from SAR 6450 to SAR 8,063 respectively as shown in (Fig 108).

	A	B	C	D	E	F
1	Year	Total site energy kWh	PCM Initial cost in KSA currency	Saving average 12.98% in kWh	Saving per year in Riyals	Cumulative annual saving in Riyals
2	1	34,511.11	27884.70	4,479.54	806.32	806.32
3	2	34,511.11	27884.70	4,479.54	806.32	1612.64
4	3	34,511.11	27884.70	4,479.54	806.32	2418.96
5	4	34,511.11	27884.70	4,479.54	806.32	3225.28
6	5	34,511.11	27884.70	4,479.54	806.32	4031.59
7	6	34,511.11	27884.70	4,479.54	806.32	4837.91
8	7	34,511.11	27884.70	4,479.54	806.32	5644.22
9	8	34,511.11	27884.70	4,479.54	806.32	6450.54
10	9	34,511.11	27884.70	4,479.54	806.32	7256.86
11	10	34,511.11	27884.70	4,479.54	806.32	8063.18
12	11	34,511.11	27884.70	4,479.54	806.32	8869.49
13	12	34,511.11	27884.70	4,479.54	806.32	9675.81
14	13	34,511.11	27884.70	4,479.54	806.32	10482.13
15	14	34,511.11	27884.70	4,479.54	806.32	11288.45
16	15	34,511.11	27884.70	4,479.54	806.32	12094.77
17	16	34,511.11	27884.70	4,479.54	806.32	12901.08
18	17	34,511.11	27884.70	4,479.54	806.32	13707.40
19	18	34,511.11	27884.70	4,479.54	806.32	14513.72
20	19	34,511.11	27884.70	4,479.54	806.32	15320.03
21	20	34,511.11	27884.70	4,479.54	806.32	16126.35
22	21	34,511.11	27884.70	4,479.54	806.32	16932.67
23	22	34,511.11	27884.70	4,479.54	806.32	17738.99
24	23	34,511.11	27884.70	4,479.54	806.32	18545.30
25	24	34,511.11	27884.70	4,479.54	806.32	19351.62
26	25	34,511.11	27884.70	4,479.54	806.32	20157.94
27	26	34,511.11	27884.70	4,479.54	806.32	20964.26
28	27	34,511.11	27884.70	4,479.54	806.32	21770.58
29	28	34,511.11	27884.70	4,479.54	806.32	22576.89
30	29	34,511.11	27884.70	4,479.54	806.32	23383.21
31	30	34,511.11	27884.70	4,479.54	806.32	24189.53

Figure 108. LCCA Model Demonstrating Proposed Pricing Based on Annual Savings.

To achieve the initial cost return within 8-10 years, the total cost of PCM in an 8-year plan based on the LCCA analysis should be SAR 6,450, which contributes to the following calculation:

- PCM purchase cost = PCM cost - PCM installation cost.
 - PCM purchase cost = SAR 6450 – SAR 1800.

- PCM purchase cost = SAR 6450 - SAR 1800 = 4,649 SAR.

The new calculated cost per ft² should be for PCM:

- **PCM price per ft² = PCM purchase cost / Wall area.**
 - PCM price per ft² = SAR 4,649 / Wall area = ?? + Installation fee per ft².
- PCM price per ft² = SAR 4,649 / 1,161 ft² = 4.00 + 1.5 = SAR 5.5 per ft².

When applying the same calculation to the 10-year plan with the cost of SAR 8063, the following pricing was found:

The new calculated coat per ft² should be for PCM:

- **Total PCM price per ft² = PCM purchase cost / Wall area.**
 - PCM price per ft² = SAR 6,263 / Wall area = ?? + Installation fee per ft².
- PCM price per ft² = SAR 6,263 / 1,161 ft² = 5.3 + 1.5 = SAR 6.9 per ft².

The proposed pricing impact on the models after applying the new prices to the LCCA model was presented visually to illustrate the impact of the initial price adjustment (Fig. 109 & 110).

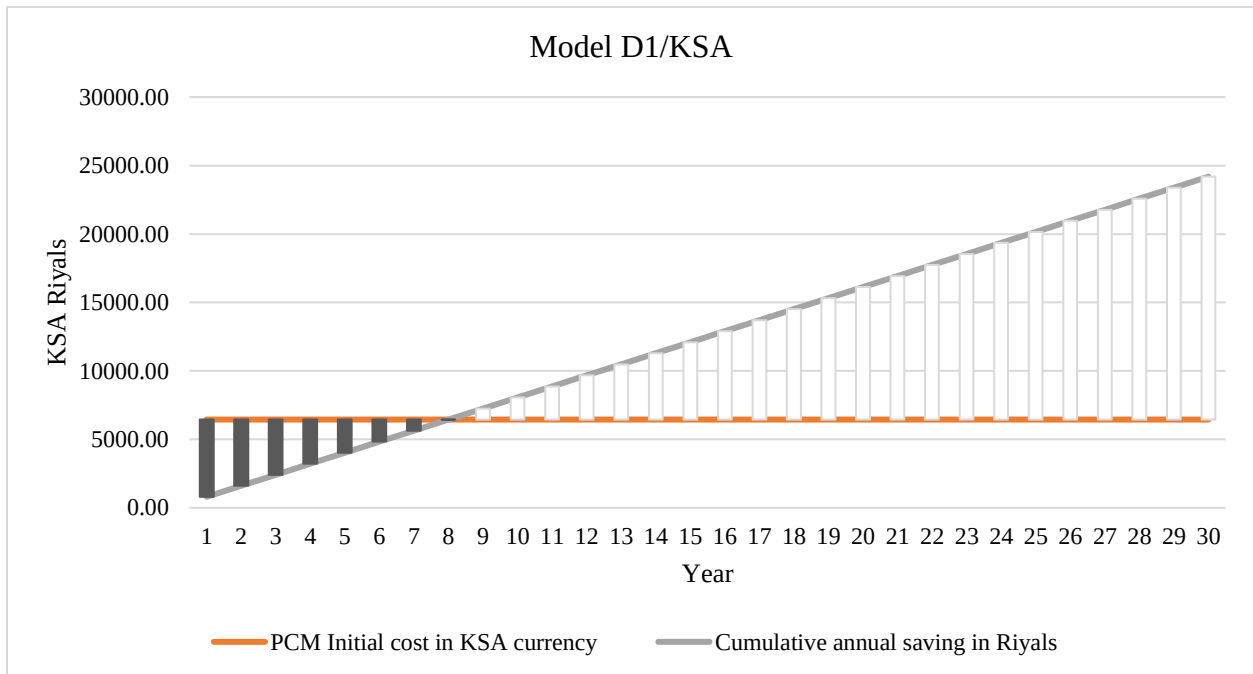


Figure 109. Model D1/KSA' PCM Proposed KSA Pricing – Investment Return 8 Years Plan.

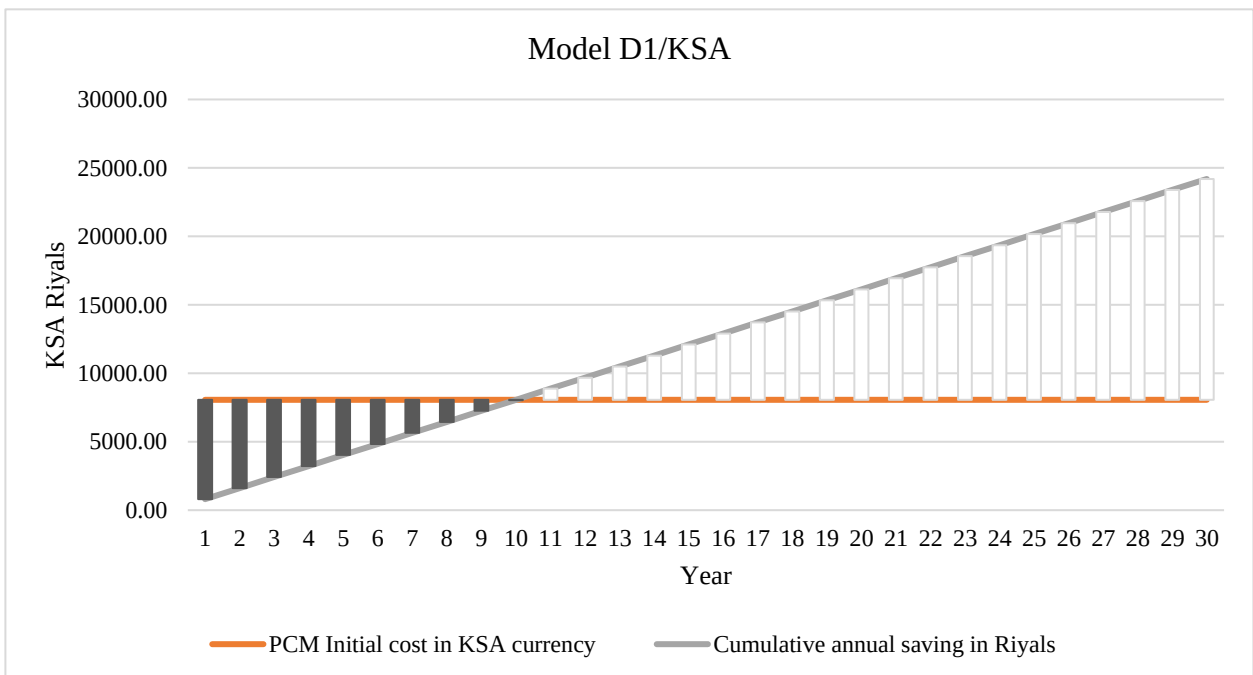


Figure 110. Model D1/KSA' PCM Proposed KSA Pricing – Investment Return 10 Years Plan.

Moving to Model D4, the application of higher thickness in Model D4 has resulted in a higher saving percentage of 13.79% on the total site energy. Nevertheless, the initial cost of the PCM is excessive since the application involves doubling the thickness of the PCM in addition to the installation cost. The Model D4 LCCA analysis has demonstrated a return plan of 38 years for the initial cost to be retrieved, falling within an unacceptable timeframe (Fig. 111 & 112).

KSA-specific factors were applied to Model D4 to create Model D4/KSA in the LCCA model, aligning it with Saudi currency and electrical rates. The LCCA demonstrated that PCM in Model D4/KSA was not able to recover the initial cost, even after 70 years, based on cumulative passive annual savings. This suggests that using PCM at a thickness of 2.0 cm is not viable. Based on this analysis, the study proposes a PCM manufacturing adjustment to reduce its price and increase savings, as discussed in the following section.

	A	B	C	D	E	F
1	Year	Total site energy kWh	PCM Initial cost in US currency	Saving average 13.79% in kWh	Saving per year in dollars	Cumulative annual saving in dollars
2	1	34,511.11	29,743.68	4,759.08	793.81	793.81
3	2	34,511.11	29,743.68	4,759.08	793.81	1587.63
4	3	34,511.11	29,743.68	4,759.08	793.81	2381.44
5	4	34,511.11	29,743.68	4,759.08	793.81	3175.26
6	5	34,511.11	29,743.68	4,759.08	793.81	3969.07
7	6	34,511.11	29,743.68	4,759.08	793.81	4762.89
8	7	34,511.11	29,743.68	4,759.08	793.81	5556.70
9	8	34,511.11	29,743.68	4,759.08	793.81	6350.52
10	9	34,511.11	29,743.68	4,759.08	793.81	7144.33
11	10	34,511.11	29,743.68	4,759.08	793.81	7938.15
12	11	34,511.11	29,743.68	4,759.08	793.81	8731.96
13	12	34,511.11	29,743.68	4,759.08	793.81	9525.78
14	13	34,511.11	29,743.68	4,759.08	793.81	10319.59
15	14	34,511.11	29,743.68	4,759.08	793.81	11113.41
16	15	34,511.11	29,743.68	4,759.08	793.81	11907.22
17	16	34,511.11	29,743.68	4,759.08	793.81	12701.04
18	17	34,511.11	29,743.68	4,759.08	793.81	13494.85
19	18	34,511.11	29,743.68	4,759.08	793.81	14288.67
20	19	34,511.11	29,743.68	4,759.08	793.81	15082.48
21	20	34,511.11	29,743.68	4,759.08	793.81	15876.30
22	21	34,511.11	29,743.68	4,759.08	793.81	16670.11
23	22	34,511.11	29,743.68	4,759.08	793.81	17463.93
24	23	34,511.11	29,743.68	4,759.08	793.81	18257.74
25	24	34,511.11	29,743.68	4,759.08	793.81	19051.56
26	25	34,511.11	29,743.68	4,759.08	793.81	19845.37
27	26	34,511.11	29,743.68	4,759.08	793.81	20639.19
28	27	34,511.11	29,743.68	4,759.08	793.81	21433.00
29	28	34,511.11	29,743.68	4,759.08	793.81	22226.82
30	29	34,511.11	29,743.68	4,759.08	793.81	23020.63
31	30	34,511.11	29,743.68	4,759.08	793.81	23814.45
32	31	34,511.11	29,743.68	4,759.08	793.81	24608.26
33	32	34,511.11	29,743.68	4,759.08	793.81	25402.08
34	33	34,511.11	29,743.68	4,759.08	793.81	26195.89
35	34	34,511.11	29,743.68	4,759.08	793.81	26989.71
36	35	34,511.11	29,743.68	4,759.08	793.81	27783.52
37	36	34,511.11	29,743.68	4,759.08	793.81	28577.34
38	37	34,511.11	29,743.68	4,759.08	793.81	29371.15
39	38	34,511.11	29,743.68	4,759.08	793.81	30164.97

Figure 111. Model D4 Cost Recovering Time Frame.

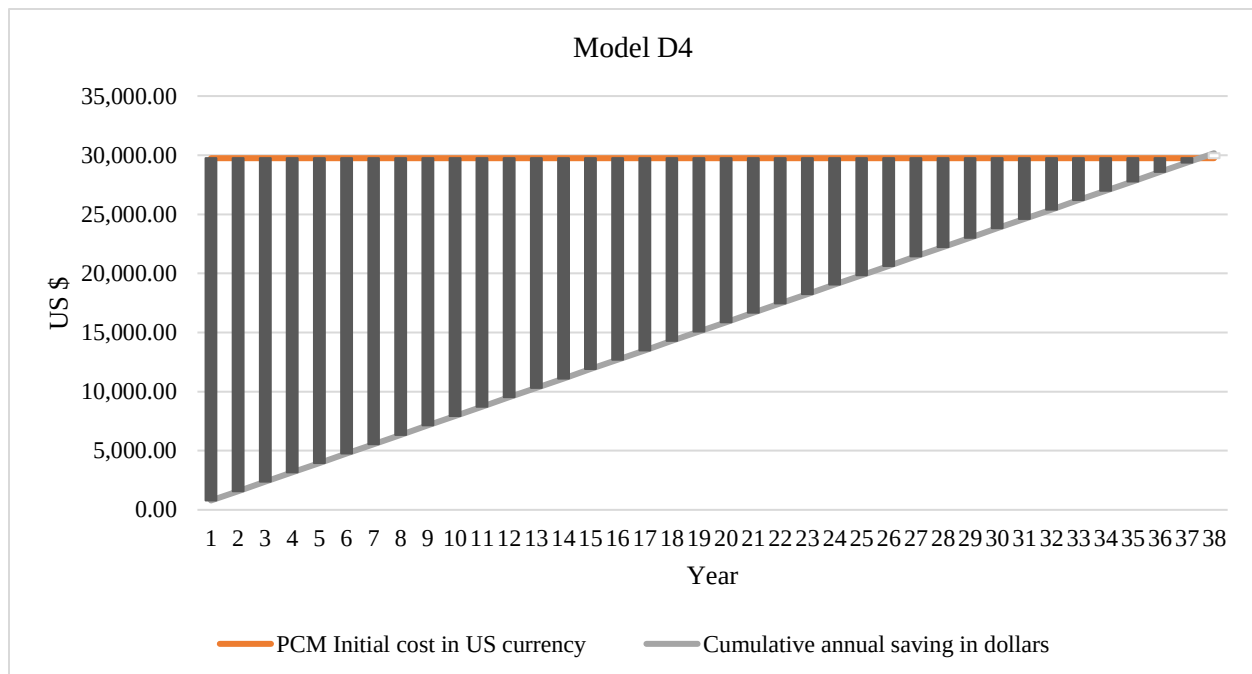


Figure 112. PCM Regular Pricing – Investment Return Years.

6.4.2 Manufacturing Proposal on Model D4 PCMs

Using PCM with a 2.0 cm thickness, as in Model D4, presented an issue with investment return, as the saving was only marginally better (by about 0.8%) compared to Model D1. This makes the application of one layer, as in Model D1, slightly more cost-effective. While Model D4 might offer slightly higher savings, it is not a suitable choice for future investment.

A recommendation for manufacturers would be to adjust their product to reduce material costs within a desirable range and obtain the 13.79% saving of PCM application, as seen in Model D4. If PCM panels are manufactured with a 2.0 cm thickness, making them single-layer panels, and if material costs increase by 30% for the extra PCM filling, the total original price could drop from \$22,543 to \$15,780. Installation costs would also fall from \$7,200 to \$1,800, reducing the total cost to \$17,580 per modular unit.

The PCM panels are capable of being manufactured with a thickness of 2.0 cm, which makes them one-layer panels with the same specifications and includes the cost of the extra filling.

If we assume that the recommendation has increased the material cost by 30% compared to the original price, the new pricing, after applying the same calculation from the previous section, reduces the PCM price from \$22,543 to \$15,780, along with a reduction in the PCM installation cost from \$7,200 to \$1,800. The new pricing makes the total cost of PCM \$17,580 per modular unit, which brings the PCM price to \$15 per ft².

The new manufactured PCM decreased price was applied in Model D4's LCCA analysis and reflected a duration of 22 years for the initial cost to recover (Fig. 113). Recovery of the initial cost is crucial. Twenty-two years is not an acceptable time frame. This study seeks to recover the cost within only 8 -10 years; therefore, a price adjustment based on the LCCA analysis was applied to the LCCA model to demonstrate the impact of price and savings in the model.

	A	B	C	D	E	F
1	Year	Total site energy kWh	PCM Initial cost in US currency	Saving average 13.79% in kWh	Saving per year in dollars	Cumulative annual saving in dollars
2	1	34,511.11	17,580	4,759.08	793.81	793.81
3	2	34,511.11	17,580	4,759.08	793.81	1587.63
4	3	34,511.11	17,580	4,759.08	793.81	2381.44
5	4	34,511.11	17,580	4,759.08	793.81	3175.26
6	5	34,511.11	17,580	4,759.08	793.81	3969.07
7	6	34,511.11	17,580	4,759.08	793.81	4762.89
8	7	34,511.11	17,580	4,759.08	793.81	5556.70
9	8	34,511.11	17,580	4,759.08	793.81	6350.52
10	9	34,511.11	17,580	4,759.08	793.81	7144.33
11	10	34,511.11	17,580	4,759.08	793.81	7938.15
12	11	34,511.11	17,580	4,759.08	793.81	8731.96
13	12	34,511.11	17,580	4,759.08	793.81	9525.78
14	13	34,511.11	17,580	4,759.08	793.81	10319.59
15	14	34,511.11	17,580	4,759.08	793.81	11113.41
16	15	34,511.11	17,580	4,759.08	793.81	11907.22
17	16	34,511.11	17,580	4,759.08	793.81	12701.04
18	17	34,511.11	17,580	4,759.08	793.81	13494.85
19	18	34,511.11	17,580	4,759.08	793.81	14288.67
20	19	34,511.11	17,580	4,759.08	793.81	15082.48
21	20	34,511.11	17,580	4,759.08	793.81	15876.30
22	21	34,511.11	17,580	4,759.08	793.81	16670.11
23	22	34,511.11	17,580	4,759.08	793.81	17463.93
24	23	34,511.11	17,580	4,759.08	793.81	18257.74
25	24	34,511.11	17,580	4,759.08	793.81	19051.56
26	25	34,511.11	17,580	4,759.08	793.81	19845.37
27	26	34,511.11	17,580	4,759.08	793.81	20639.19
28	27	34,511.11	17,580	4,759.08	793.81	21433.00
29	28	34,511.11	17,580	4,759.08	793.81	22226.82
30	29	34,511.11	17,580	4,759.08	793.81	23020.63
31	30	34,511.11	17,580	4,759.08	793.81	23814.45

Figure 113. Model D4 Cost Recovering Time Frame after Manufacturing Proposal Application.

The LCCA analysis for Model D4 demonstrated that more than 10 years are required to recover the initial cost. The research previously indicated that the aim was to demonstrate all the possibilities of taking advantage of PCM applications. Model D4 could be a viable option if the recovery period falls within the 8-10 year range. Based on the analysis, the price of Model D4 must be between \$6,350 and \$7,938 to meet cumulative savings targets (Fig. 114).

	A	B	C	D	E	F
	Year	Total site energy kWh	PCM Initial cost in US currency	Saving average 13.79% in kWh	Saving per year in dollars	Cumulative annual saving in dollars
1	1	34,511.11	17,580	4,759.08	793.81	793.81
2	2	34,511.11	17,580	4,759.08	793.81	1587.63
3	3	34,511.11	17,580	4,759.08	793.81	2381.44
4	4	34,511.11	17,580	4,759.08	793.81	3175.26
5	5	34,511.11	17,580	4,759.08	793.81	3969.07
6	6	34,511.11	17,580	4,759.08	793.81	4762.89
7	7	34,511.11	17,580	4,759.08	793.81	5556.70
8	8	34,511.11	17,580	4,759.08	793.81	6350.52
9	9	34,511.11	17,580	4,759.08	793.81	7144.33
10	10	34,511.11	17,580	4,759.08	793.81	7938.15
11	11	34,511.11	17,580	4,759.08	793.81	8731.96
12	12	34,511.11	17,580	4,759.08	793.81	9525.78
13	13	34,511.11	17,580	4,759.08	793.81	10319.59
14	14	34,511.11	17,580	4,759.08	793.81	11113.41
15	15	34,511.11	17,580	4,759.08	793.81	11907.22
16	16	34,511.11	17,580	4,759.08	793.81	12701.04
17	17	34,511.11	17,580	4,759.08	793.81	13494.85
18	18	34,511.11	17,580	4,759.08	793.81	14288.67
19	19	34,511.11	17,580	4,759.08	793.81	15082.48
20	20	34,511.11	17,580	4,759.08	793.81	15876.30
21	21	34,511.11	17,580	4,759.08	793.81	16670.11
22	22	34,511.11	17,580	4,759.08	793.81	17463.93
23	23	34,511.11	17,580	4,759.08	793.81	18257.74
24	24	34,511.11	17,580	4,759.08	793.81	19051.56
25	25	34,511.11	17,580	4,759.08	793.81	19845.37
26	26	34,511.11	17,580	4,759.08	793.81	20639.19
27	27	34,511.11	17,580	4,759.08	793.81	21433.00
28	28	34,511.11	17,580	4,759.08	793.81	22226.82
29	29	34,511.11	17,580	4,759.08	793.81	23020.63
30	30	34,511.11	17,580	4,759.08	793.81	23814.45

Figure 114. Model D4 8-10 Years Applicable Price Range.

For Model D4/KSA, a price adjustment is also necessary to make the 2.0 cm PCM layer desirable and within a feasible price range for KSA investments. According to the LCCA, the material price should fall between SAR 6,853 and SAR 8,566 to meet the 8-10 year payback period. For an 8-year plan, the PCM price should be adjusted to SAR 5.9 per ft² plus installation costs. For a 10-year plan, the price should be around SAR 6.8 per ft². These adjustments are crucial

for demonstrating financial benefits from PCM implementation within a reasonable time frame (Fig. 115).

	A	B	C	D	E	F
1	Year	Total site energy kWh	PCM Initial cost in KSA currency	Saving average 13.79% in kWh	Saving per year in SAR	Cumulative annual saving in SAR
2	1	34,511.11	65,925	4,759.08	856.63	856.63
3	2	34,511.11	65,925	4,759.08	856.63	1713.26
4	3	34,511.11	65,925	4,759.08	856.63	2569.89
5	4	34,511.11	65,925	4,759.08	856.63	3426.52
6	5	34,511.11	65,925	4,759.08	856.63	4283.15
7	6	34,511.11	65,925	4,759.08	856.63	5139.78
8	7	34,511.11	65,925	4,759.08	856.63	5996.41
9	8	34,511.11	65,925	4,759.08	856.63	6853.04
10	9	34,511.11	65,925	4,759.08	856.63	7709.67
11	10	34,511.11	65,925	4,759.08	856.63	8566.30
12	11	34,511.11	65,925	4,759.08	856.63	9422.93
13	12	34,511.11	65,925	4,759.08	856.63	10279.56
14	13	34,511.11	65,925	4,759.08	856.63	11136.19
15	14	34,511.11	65,925	4,759.08	856.63	11992.82
16	15	34,511.11	65,925	4,759.08	856.63	12849.45
17	16	34,511.11	65,925	4,759.08	856.63	13706.08
18	17	34,511.11	65,925	4,759.08	856.63	14562.71
19	18	34,511.11	65,925	4,759.08	856.63	15419.34
20	19	34,511.11	65,925	4,759.08	856.63	16275.97
21	20	34,511.11	65,925	4,759.08	856.63	17132.60
22	21	34,511.11	65,925	4,759.08	856.63	17989.23
23	22	34,511.11	65,925	4,759.08	856.63	18845.86
24	23	34,511.11	65,925	4,759.08	856.63	19702.49
25	24	34,511.11	65,925	4,759.08	856.63	20559.12
26	25	34,511.11	65,925	4,759.08	856.63	21415.75
27	26	34,511.11	65,925	4,759.08	856.63	22272.38
28	27	34,511.11	65,925	4,759.08	856.63	23129.01
29	28	34,511.11	65,925	4,759.08	856.63	23985.64
30	29	34,511.11	65,925	4,759.08	856.63	24842.27
31	30	34,511.11	65,925	4,759.08	856.63	25698.90

Figure 115. Model D4/KSA 8-10 Years Applicable Price Range.

These pricing adjustments illustrate the limits for PCM materials to be feasible and desirable. Incorporating these prices into the LCCA model shows that an 8-year plan would generate future savings of SAR 17.4K over the next 22 years, while a 10-year plan would yield SAR 15.8K in future savings as shown in Figure. 116 & 117.

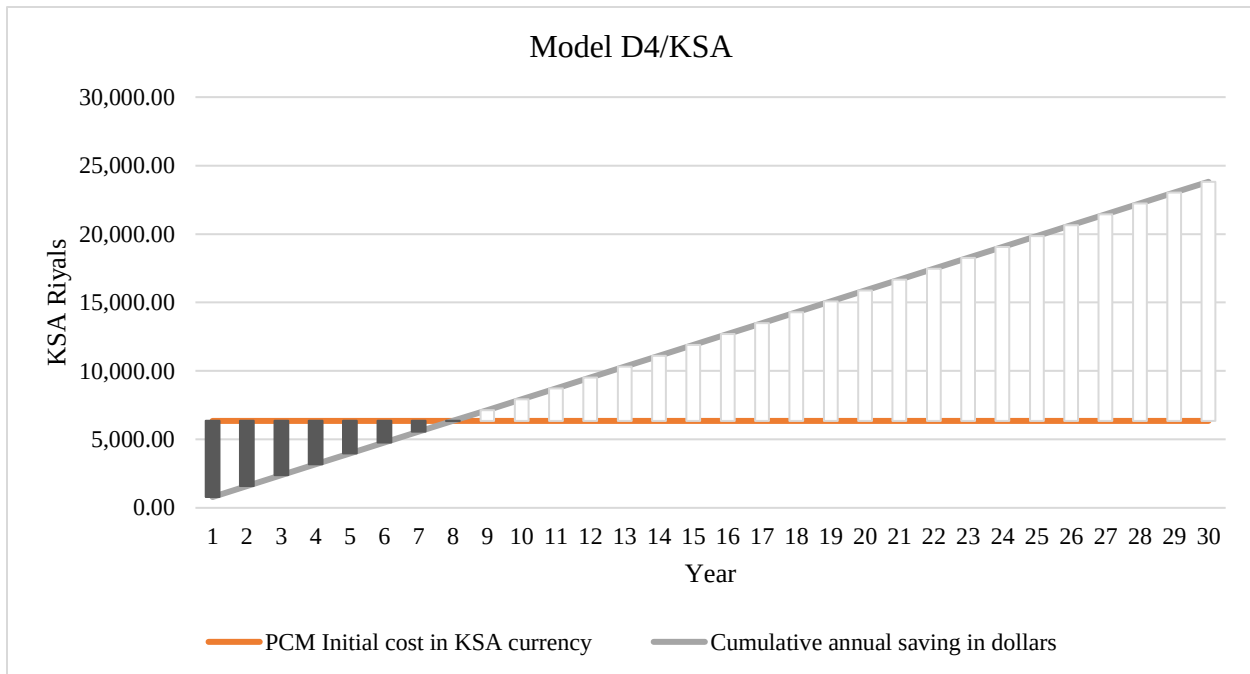


Figure 116. Model D4/KSA' PCM Proposed Pricing – Investment Return 8 Years Plan.

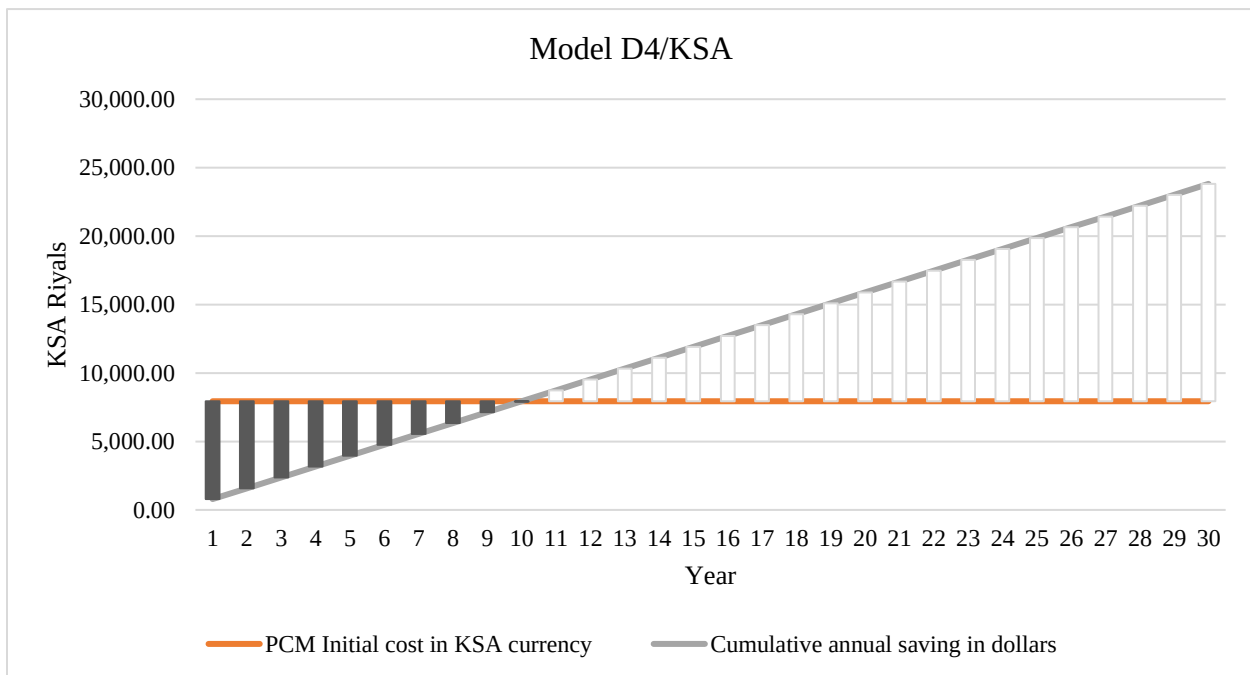


Figure 117. Model D4/KSA' PCM Proposed Pricing – Investment Return 10 Years Plan.

Model D1 was analyzed under a typical scenario with the lowest PCM thickness which resulted in a considerable annual total site energy saving of 12.98%. The initial cost was recovered within 10 years and resulted in passive annual savings of \$10,000 over the next 20 years. This model highlights the potential of PCM applications with convenient initial costs and substantial long-term savings.

Model D1/KSA analysis provided a forecast of a 30-year timeframe for the initial cost to recover. The analysis recommends adjusting the initial PCM costs to fall between SAR 6450 and SAR 8,063 based on the obtained cumulative annual savings. The proposed price is to ensure that the cost is recovered within 8 to 10 years, to make PCM a favorable option for the Saudi construction industry.

On the other hand, Model D4 with (2.0 cm) PCM thickness presented less favorable outcomes. Despite achieving higher annual energy savings of 13.79%, the substantial initial cost extends the payback period to over 30 years in the context of the US and beyond 40 years for Model D4/KSA. The outcomes of using (2.0 cm) PCM thickness are undesirable within the current price range and necessitate the proposed price adjustment.

6.4.3 Inflation in Electrical Rate Application

This section addresses inflation in electricity rates and accounts for future uncertainties. In view of the fact that Saudi Arabia lacks detailed historical data on electrical rates, an average increase of 2.67% was used in the LCCA models. The cost models in this section align with real-world inflation trends in electricity pricing.

- **D1 Models**

The application of electricity rate inflation in Model D1 reduced the investment return time frame from 10 to 9 years and increased future savings over the following 21 years to \$26.2K which in return highlights PCM's benefits as electricity rates rise (Fig. 118). In Model D1/KSA, inflation reduced the recovery period from 35 to 25 years, although it still did not meet the proposed recovery time frame. The LCCA visualization on the model demonstrates the importance of applying the study's price proposal to Model D1/KSA. The model indicated an unacceptable time frame for initial cost recovery from the annual savings and illustrates the delayed benefits of future savings as passive income after the costs have been recovered (Fig. 119).

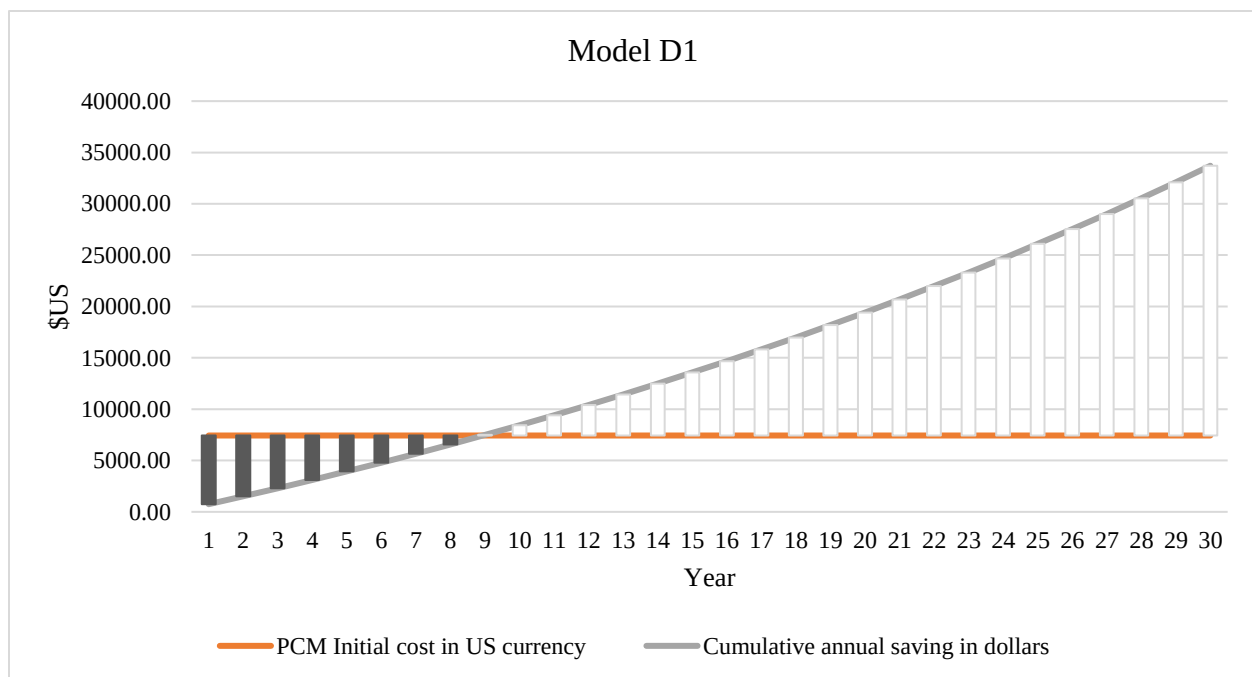


Figure 118. The Application of an Annual 2.67% Increase in the Electrical Rate.

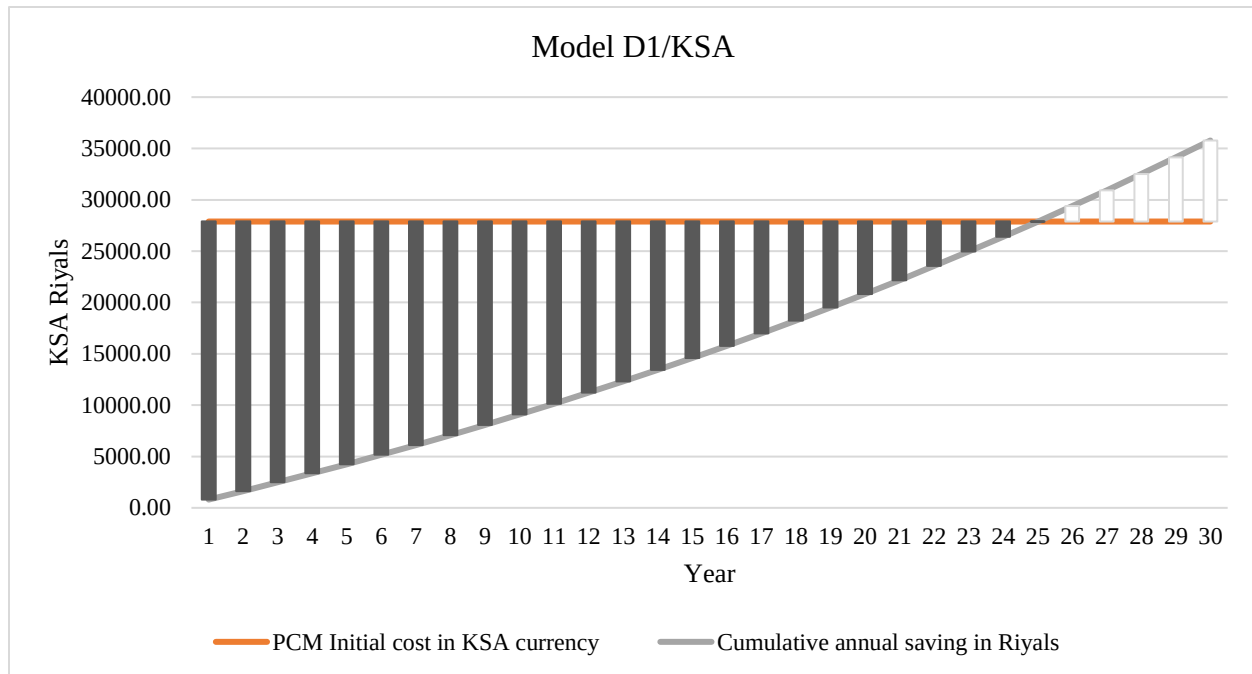


Figure 119. The Application of an Annual 2.67% Increase in the Electrical Rate.

In this section, the addition of electrical rate inflation to the proposed PCM prices in Model D1/KSA led to the following outcomes:

1. The 8-year plan reflected a significant investment return with the adjusted price. The LCCA model indicated that the initial cost would be recovered in 7.6 years and generated future savings of SAR 29.1K over the following 23.5 years (Fig. 120).
2. The proposed price for the 10-year plan also reflected a strong investment return, reduced the recovery period from 10 years to 9 years, and provided future savings of SAR 27.6K over the subsequent 21 years (Fig. 121). The application of PCM is very dependent on the price adjustment to be worth the cost as an investment, as shown in KSA models.

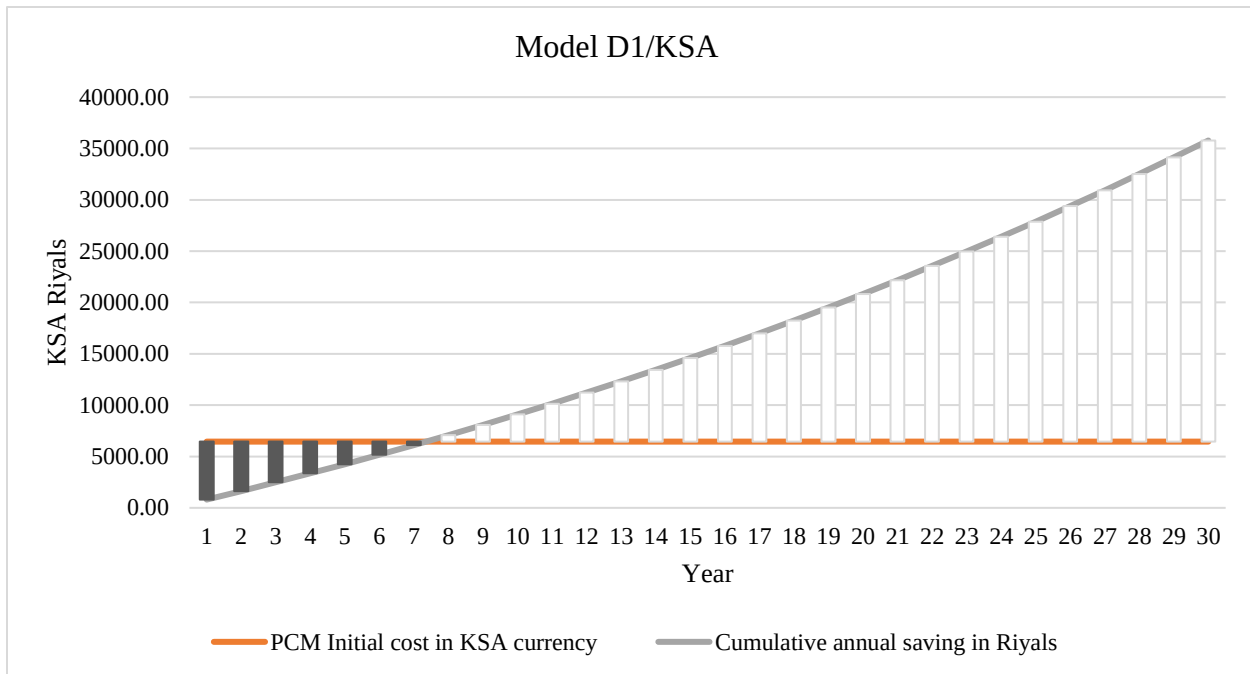


Figure 120. Model D1/KSA's Proposed Pricing: 8-Year Plan Difference After the Application of Electrical Rate Inflation.

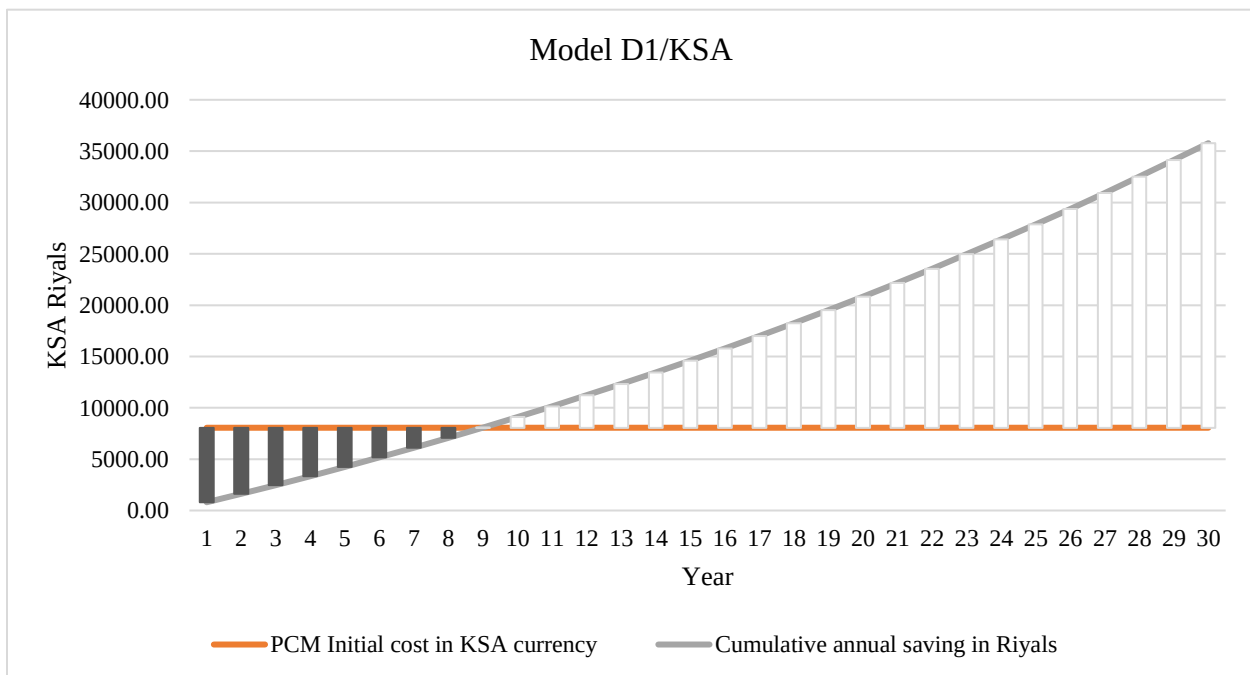


Figure 121. Model D1/KSA's Proposed Pricing: 10-Year Plan Difference After the Application of Electrical Rate Inflation.

- **D4 Models**

Even after applying the electrical rate inflation to the LCCA model in this group, the investment return timeframe remained excessive with regular pricing. Although the timeframe for investment return was reduced, it is still considered too extreme for PCM to be a viable investment. The return on investment was shortened by 22.1 years, but this reduction is still insufficient for the industry to adopt PCM (Fig. 122).

A similar conclusion was anticipated for Model D4/KSA, as Model D4 consistently demonstrated more favorable investment returns but remained expensive in the US market. The model showed a significant timeframe exceeding 30 years at the normal price rate. The timeframe decreased noticeably after applying the electricity inflation rate but remains too prolonged for the industry to consider PCM adoption in KSA (Fig. 123).

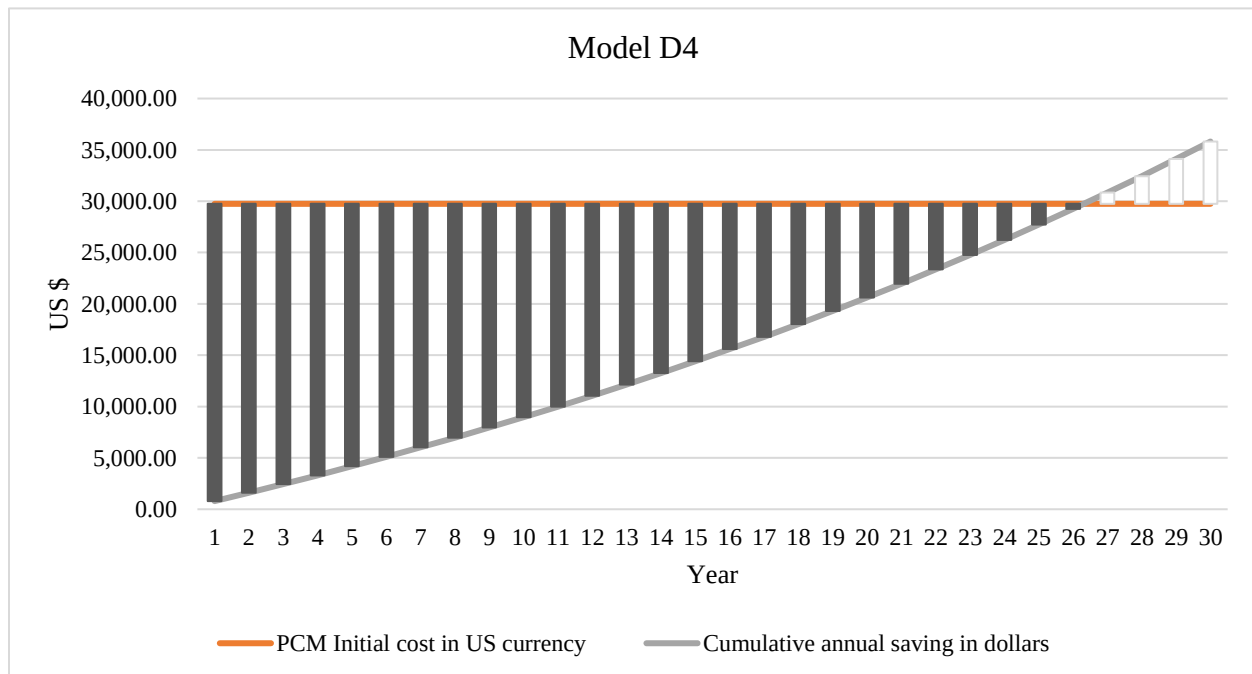


Figure 122. The Application of an Annual 2.67% Increase in the Electrical Rate.

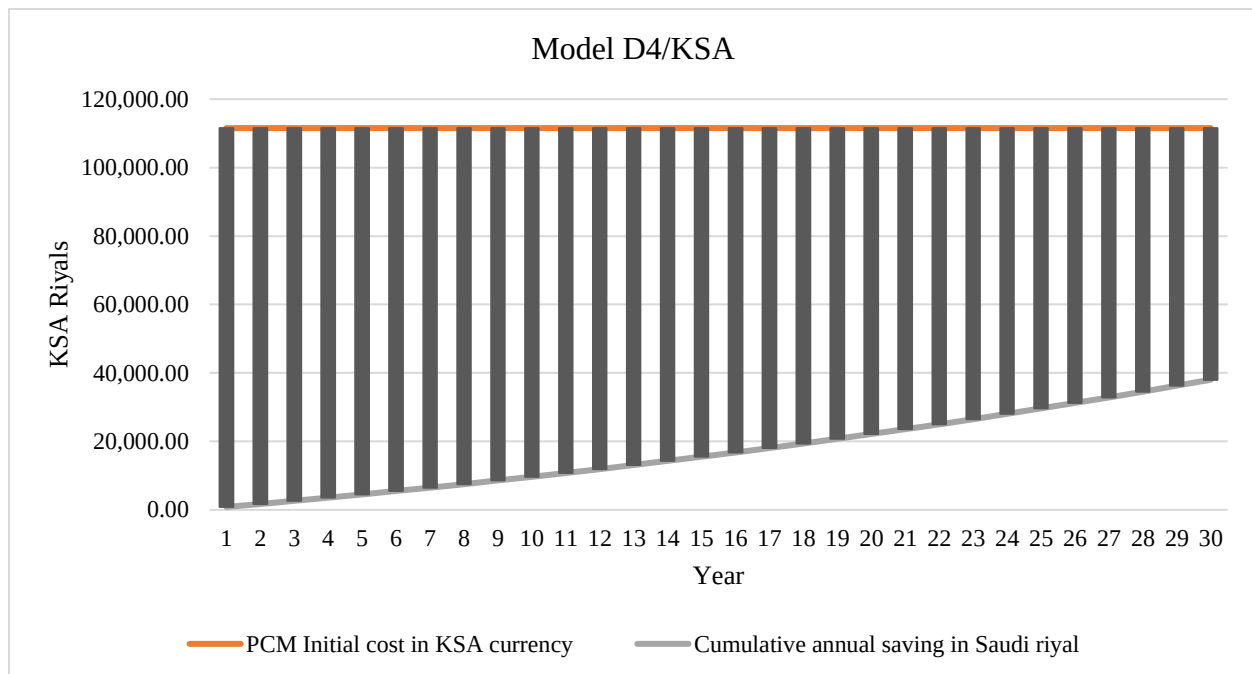


Figure 123. The Application of an Annual 2.67% Increase in the Electrical Rate.

The study applied the electrical inflation rate to the models with proposed pricing in group D4. This inflation assumption reduced the return on investment period from the planned 8 years to 7 years and increased projected future savings to \$29.3K over the next 23 years (Fig. 124). Similarly, the proposed pricing for the 10-year plan reduced the payback period to 8.3 years, with projected savings of \$26.8K over the following 20 years (Fig. 125). These findings are based on the LCCA model, which provides the industry and manufacturers with a clearer understanding of the limitations and opportunities of utilizing PCM in the construction sector under the proposed pricing structure.

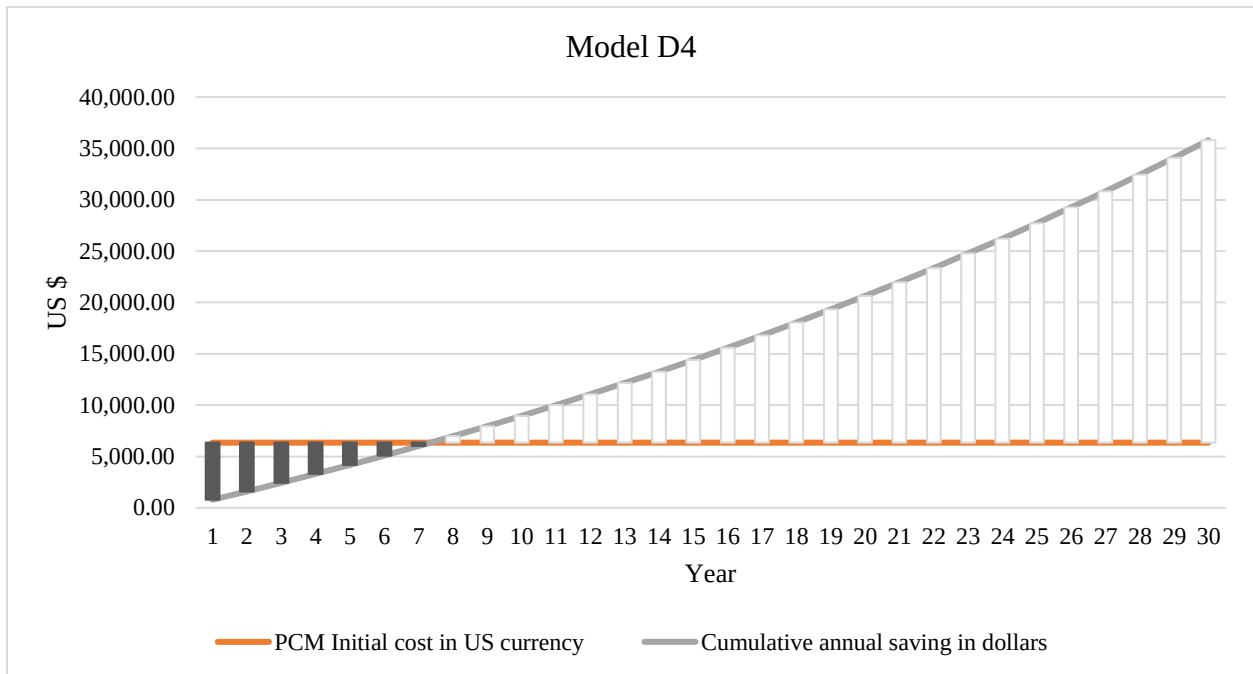


Figure 124. Model D4 Proposed Pricing: 8-Year Plan Difference After the Application of Electrical Rate Inflation.

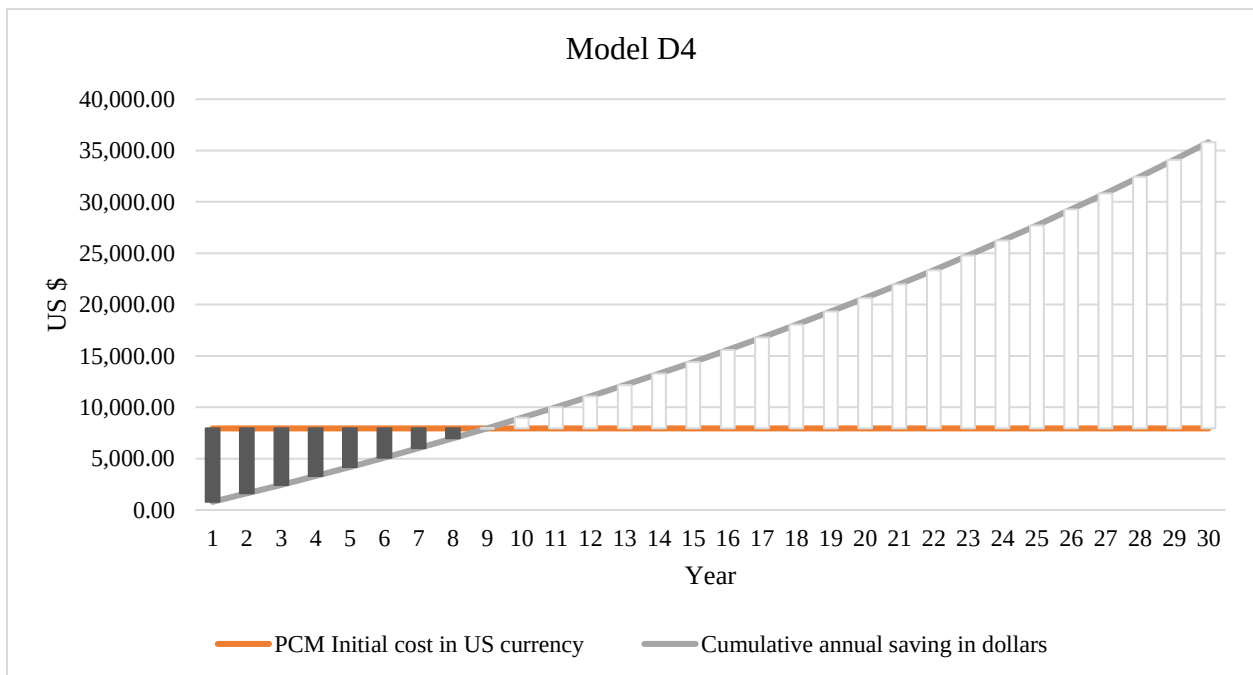


Figure 125. Model D4 Proposed Pricing: 10-Year Plan Difference After the Application of Electrical Rate Inflation.

In the Model D4/KSA case, the standard pricing resulted in a payback period exceeding 60 years, even with the incorporation of an annual inflation rate. However, the study will apply the inflation rate to the proposed pricing for Model D4/KSA to demonstrate the difference when adjusted pricing is used and to emphasize the importance of this adjustment for the industry. The application of the proposed pricing in both investment return plans has shown a reduction of about one year in the payback period for both the 8 and 10 year plans (Figs. 126, 127). Additionally, projected savings over the next 22 years increased from SAR 31K for the desired 8-year plan and approximately SAR 29.4K for the 10-year plan.

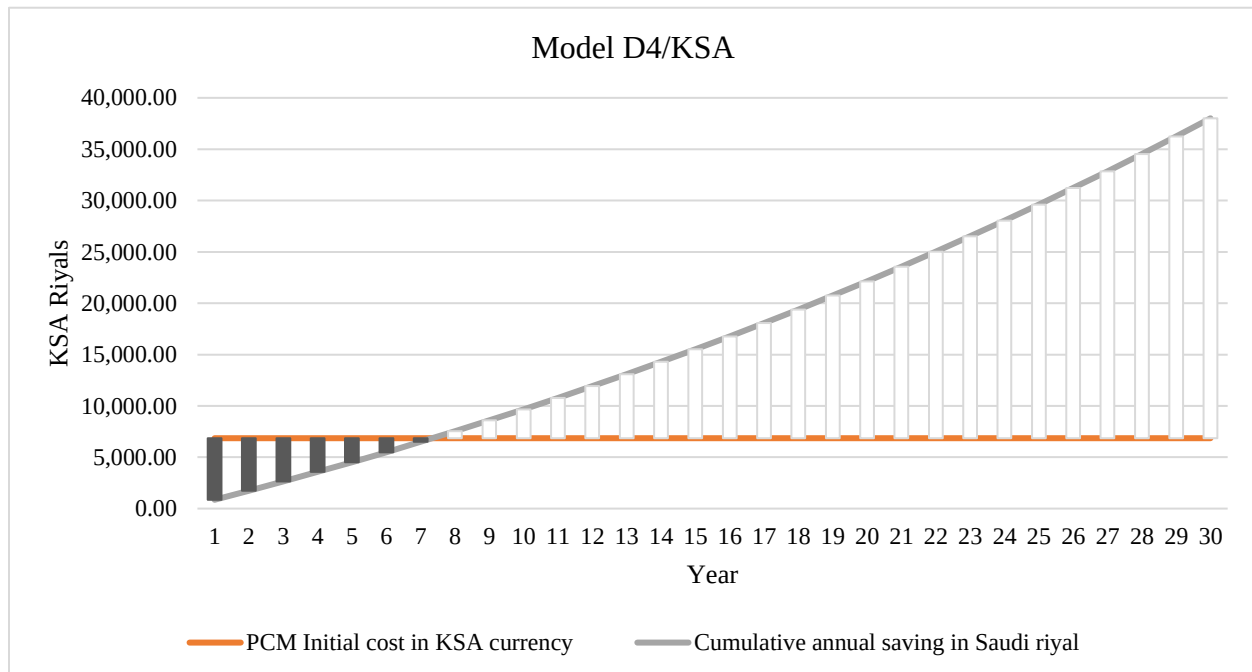


Figure 126. Model D4/KSA Proposed Pricing: 8-Year Plan Difference After the Application of Electrical Rate Inflation.

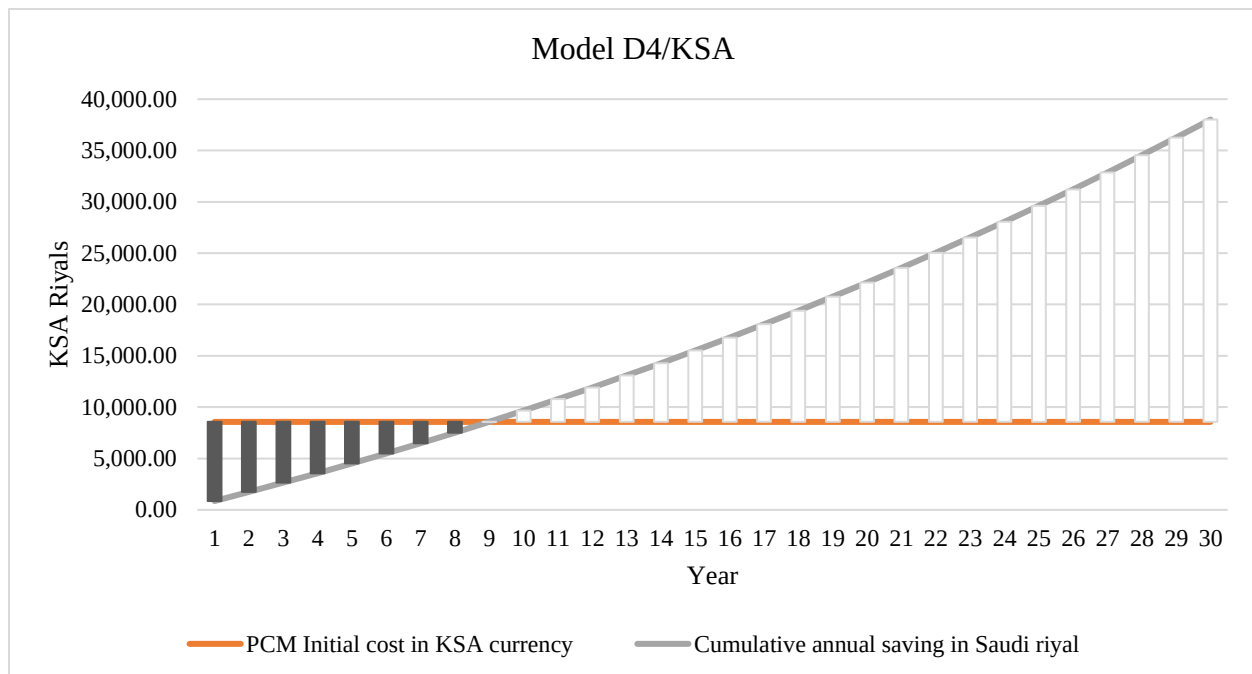


Figure 127. Model D4/KSA Proposed Pricing: 10-Year Plan Difference After the Application of Electrical Rate Inflation.

6.4.4 Inflation in Initial Cost Rate Application

This study addresses the impact of inflation on the initial cost of PCM applications during this phase by using US inflation rates from 2010 to 2023. This step calculates the average annual increase in initial cost, which reflects a dynamic and forward-looking approach. An average annual increase of 2.87% was calculated and applied to the LCCA model structure to account for the unpredictable nature of inflation on material supply and production costs. The graphical analysis will differ in this section, as it aims to demonstrate the difference between the fixed initial cost after application and the price increase due to inflation over the years, along with the cumulative savings gained from the PCM application.

- **Model D1**

The inflation rate applied demonstrated passive savings on the initial cost in subsequent years. The orange line illustrates the increase in the initial cost starting from the second year and continuing to 30 years. Early PCM application results in an average saving of \$9,815, in addition to future savings from energy reduction, as shown by the light-yellow line, with a total of \$14,943 in future passive savings while maintaining the fixed electrical rate (Fig. 128).

The benefits of PCM application increase when considering both inflation in initial costs and electrical rates. This impact increased the future return on investment from \$14,943 to \$27,853 by decreasing the return time frame and extending the passive savings period from 20 to 22 years (Fig. 129). In the next section, the same factors were applied to Model D4 to illustrate the impact of inflation on the LCCA analysis.

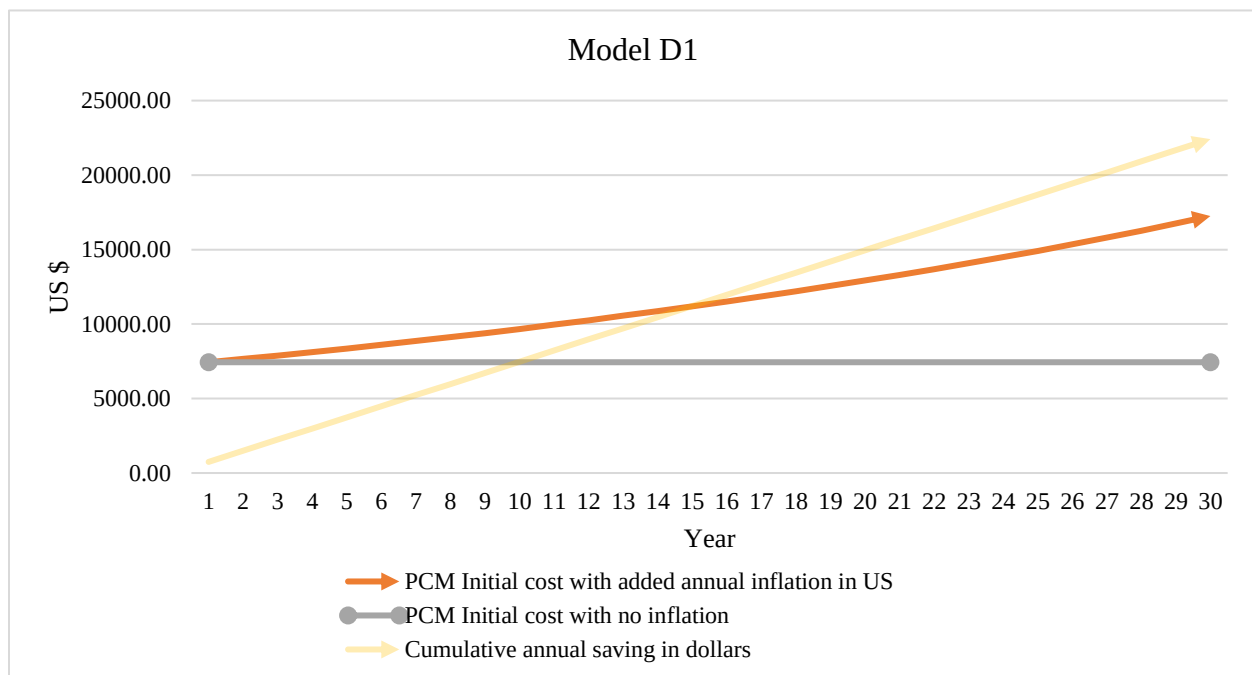


Figure 128. Model D1 Visualization Under the Impact of Initial Cost Inflation.

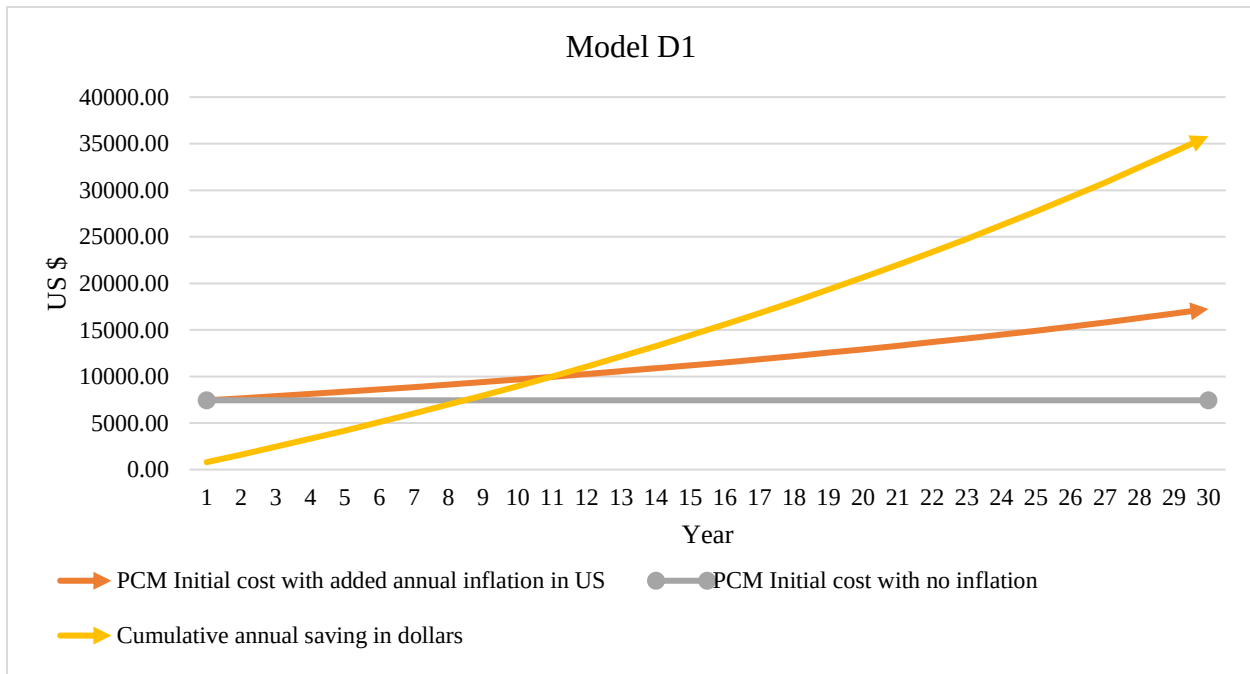


Figure 129. Model D1 Visualization Under the Impact of Electrical and Initial Cost Inflation.

- **Model D4**

Model D4 reflected a high initial cost even with the added value of additional savings, which produces an undesirable option in view of the fact that the cost outweighed the forecasted savings. A significant gap is reflected between the fixed initial cost (gray line) with no inflation and the future annual passive savings (yellow line) provided by PCM application, which reflected that the impact of inflation on the initial cost became less important compared to the high initial cost (orange line), as shown in Figure 130. While the application of PCM would have yielded benefits in the future when electricity rates increased, making it a more desirable and reliable investment, the current analysis was less favorable.

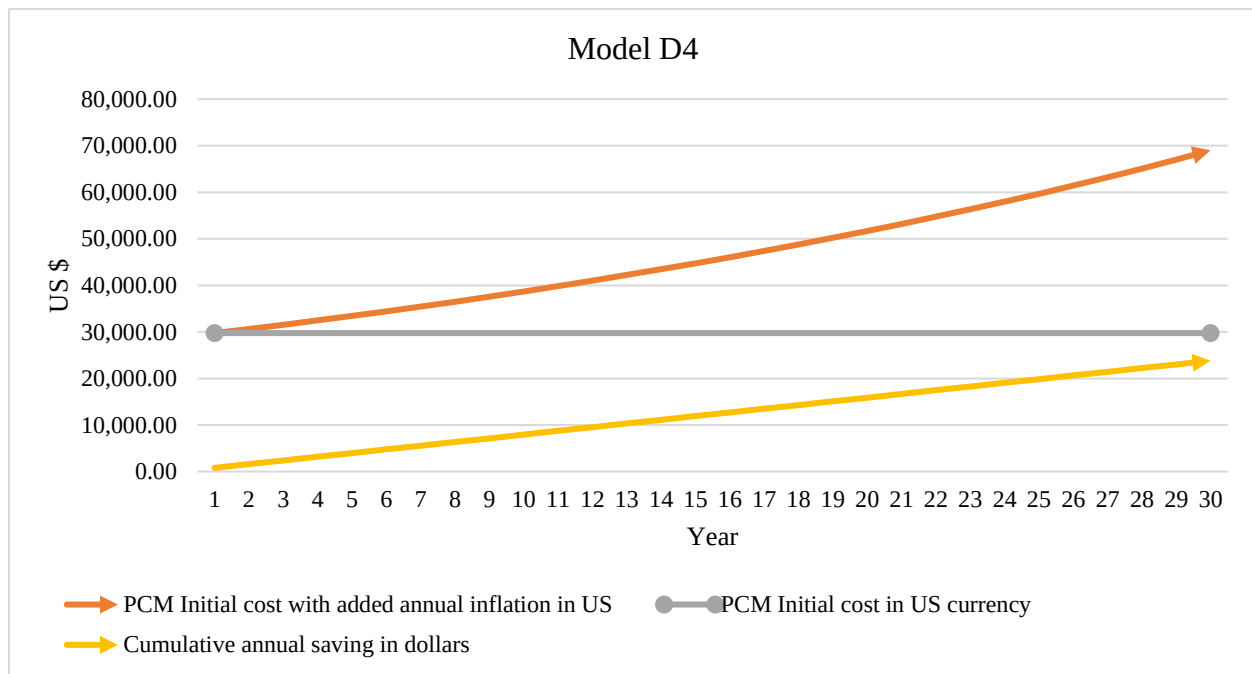


Figure 130. Model D4 Visualization Under the Impact of Initial Cost Inflation.

The utilization of PCM in Model D4 remained challenging and not without risks even after incorporating the electricity inflation rate into the LCCA model. The initial cost would take about 27 years to recover after applying the electricity rate inflation. The projection reflected that PCM could potentially become a desirable option only if there were a substantial increase in the electrical rate from about 16.8 to 60 cents per kWh, which would yield a return on investment in at least 10 years. The results demonstrated the importance and impact of the proposed pricing and manufacturing adjustments, as supported by the analysis in this study (Fig. 131).

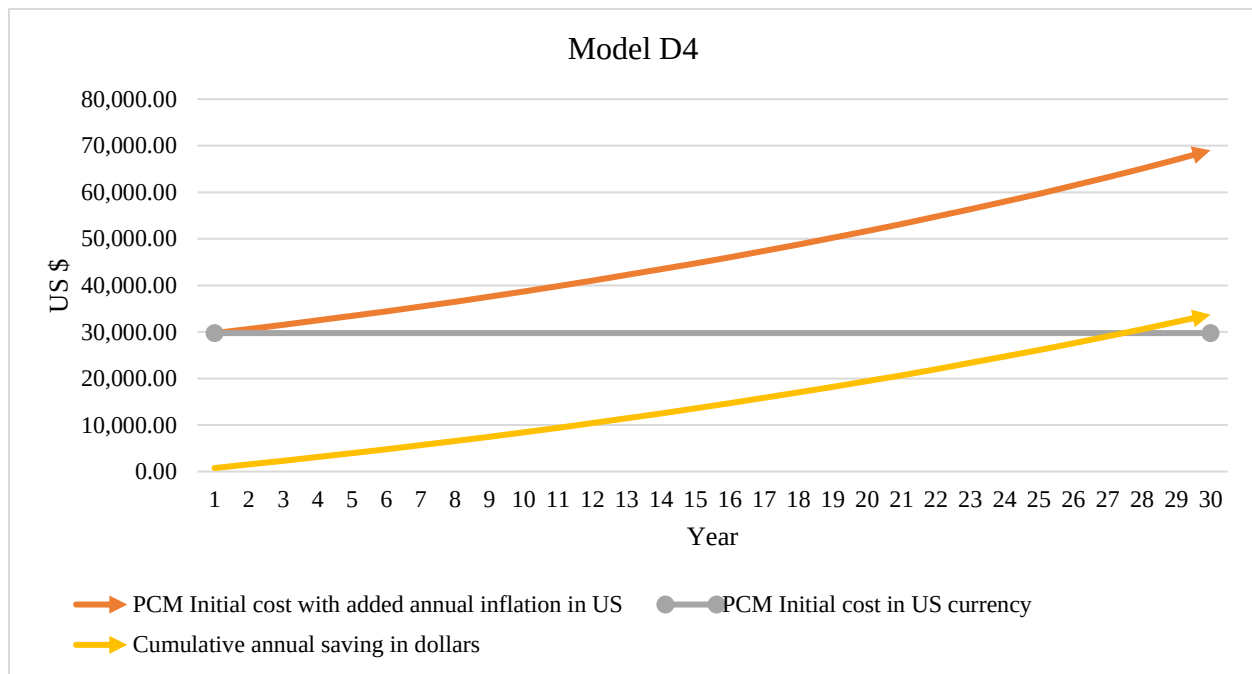


Figure 131. Model D4 Visualization Under the Impact of Electrical and Initial Cost Inflation.

On the other hand, Model D4's proposed pricing of the 8-year plan was analyzed with the inflation rate applied, which added a passive saving to the initial cost over the subsequent 29 years. The orange line illustrates the increase in the initial cost starting from the second year under the influence of the added inflation rate. The initial cost in the first year remains constant and, based on the LCCA, results in an average saving of \$8,382. Additionally, future energy savings are shown by the light-yellow line, amounting to \$17,361 in future passive savings while maintaining a fixed electrical rate (Fig. 132). When applying both inflation to the initial cost and electrical rates, the future return on investment increases from \$17,361 to \$28,832 by decreasing the return time frame and extending the passive saving return period by 22 years (Fig. 133).

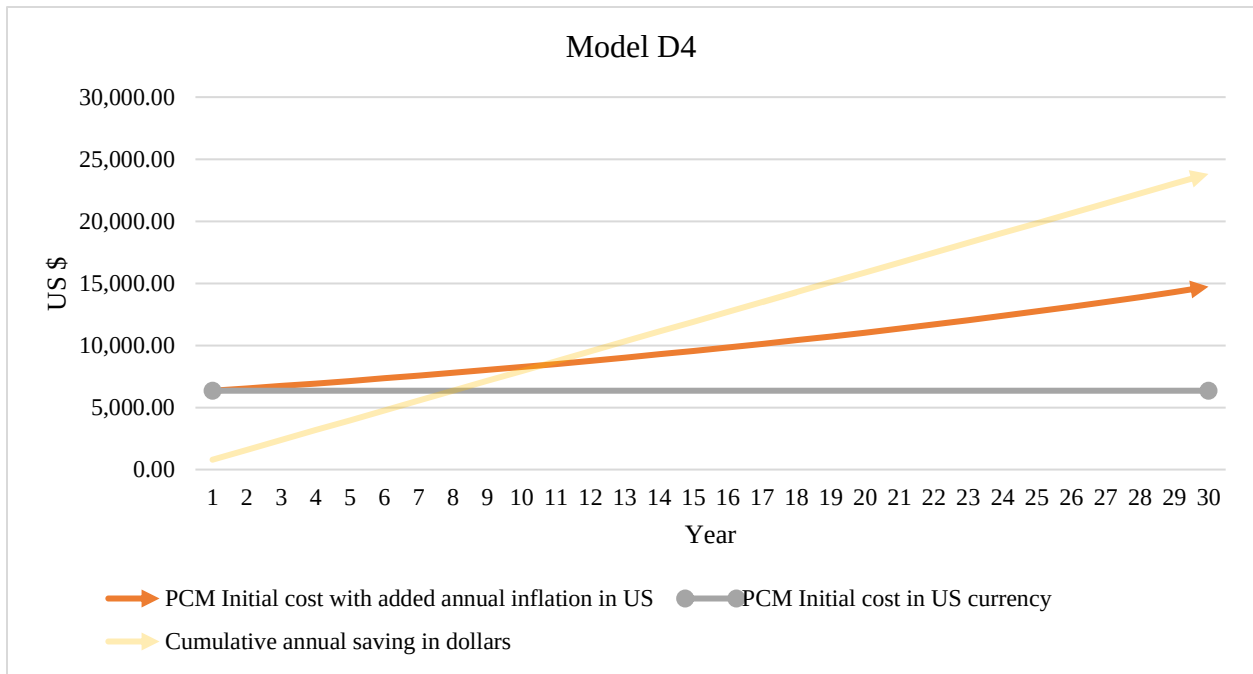


Figure 132. Model D4 Proposed Pricing: 8-Year Plan Difference After the Application of Inflation Rate.

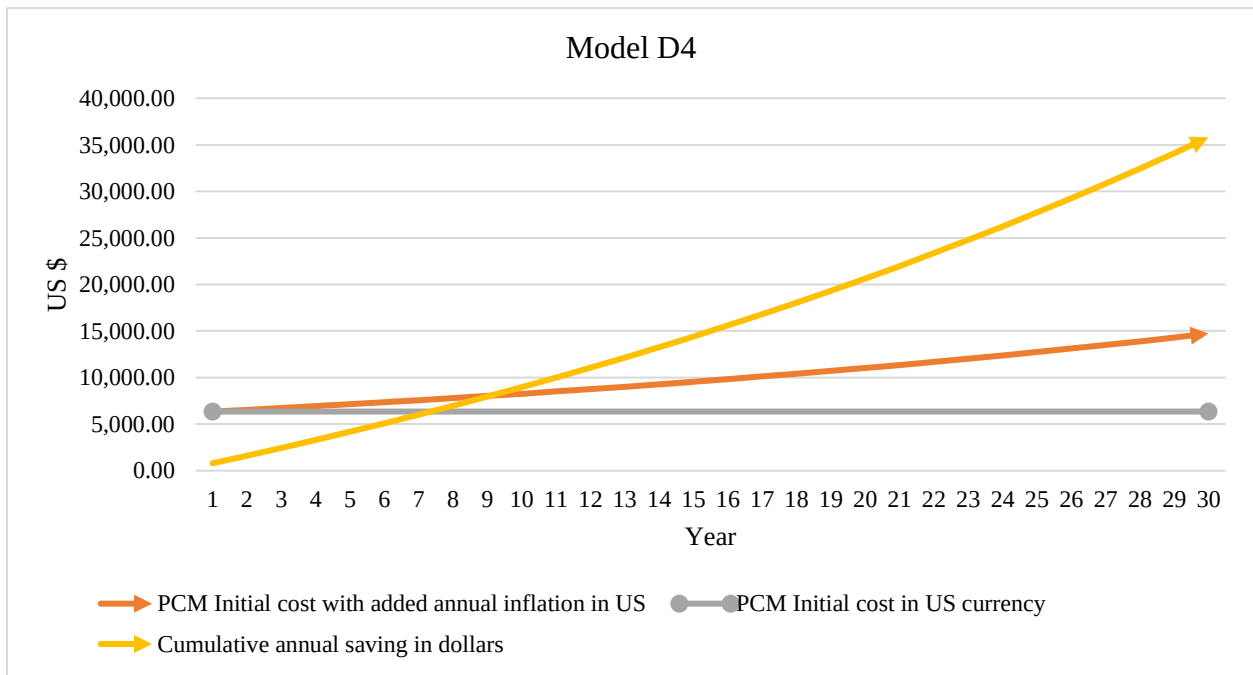


Figure 133. Model D4 Proposed Pricing: 8-Year Plan Difference After the Application of Inflation & Electrical Rate.

The 10-year plan underwent the same analysis with the inflation rate applied, which yielded the following advantages. According to the LCCA, the increase in initial cost resulted in an average saving of \$10,478. Additionally, energy savings presented by the light-yellow line, amounted to \$15,876 in future passive savings while maintaining a fixed electrical rate (Fig. 134). Meanwhile, applying inflation to both the initial cost and electrical rates increased the future return on investment by \$27,835, shortening the return time frame and extending the passive savings return period by 1.4 years (Fig. 135).

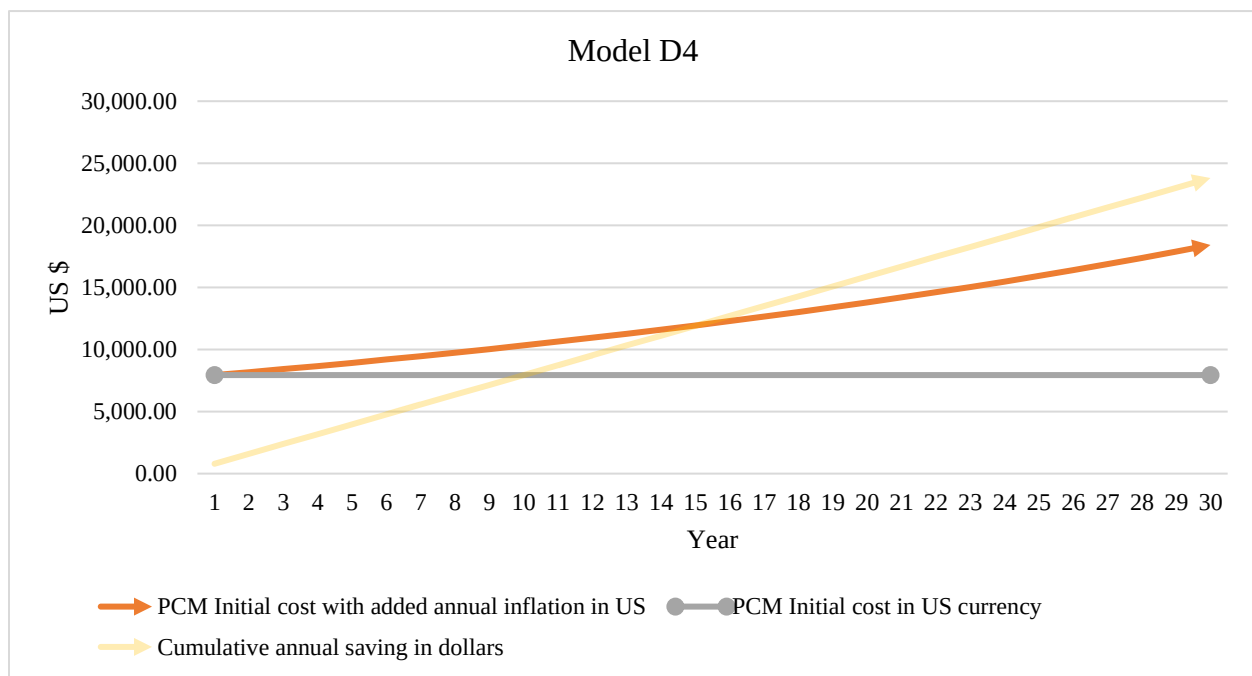


Figure 134. Model D4 Proposed Pricing: 10-Year Plan Difference After the Application of Inflation Rate.

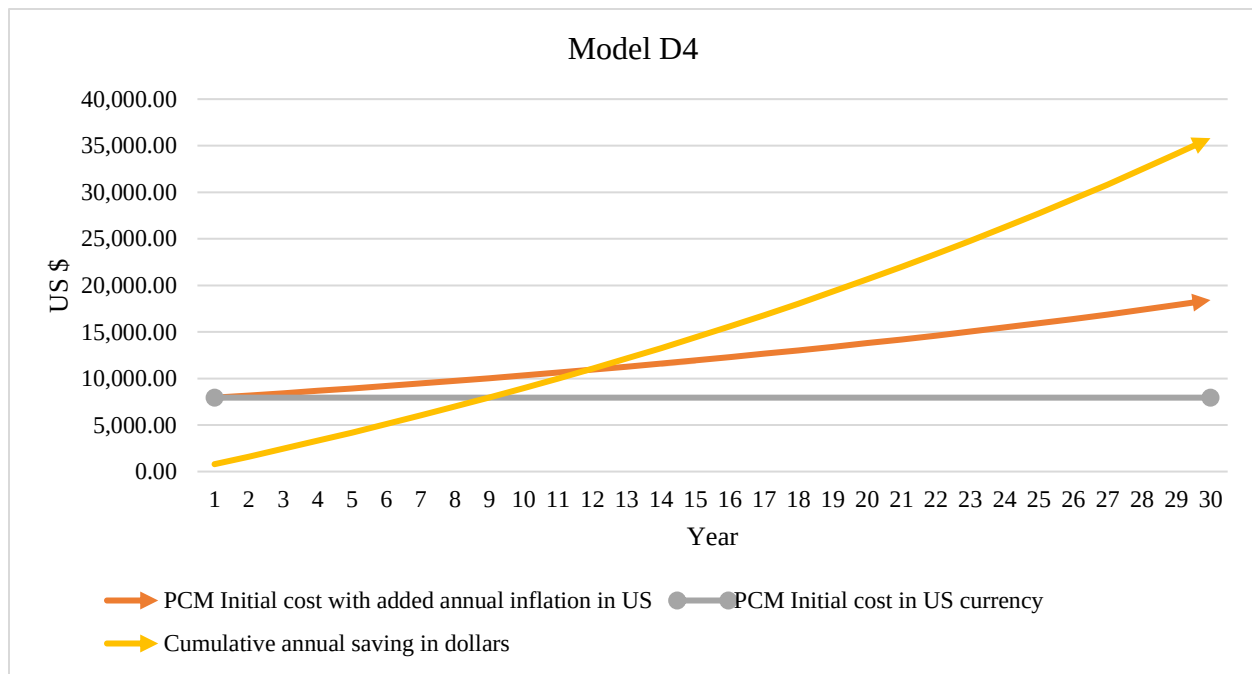


Figure 135. Model D4 Proposed Pricing: 10-Year Plan Difference After the Application of Inflation & Electrical Rate.

In the previous section, Model D4/KSA, based on the LCCA results, reflected that the application of PCM could not recover the initial cost even after 70 years. This indicated that applying inflation and electrical rates had no significant impact. Therefore, the study will proceed with the proposed pricing models for Model D4/KSA.

Starting with the 8-year plan, the LCCA results indicated an average saving of SAR 9,046 from the cost increase over the next 29 years. Additionally, the forecasted energy savings presented by the light yellow line equate to SAR 18,845 in future passive savings (Fig. 136). The future return on investment increased from SAR 18,845 to SAR 30,480 after accounting for inflation in both the initial cost and electrical rates and by extending the savings period (Fig. 137).

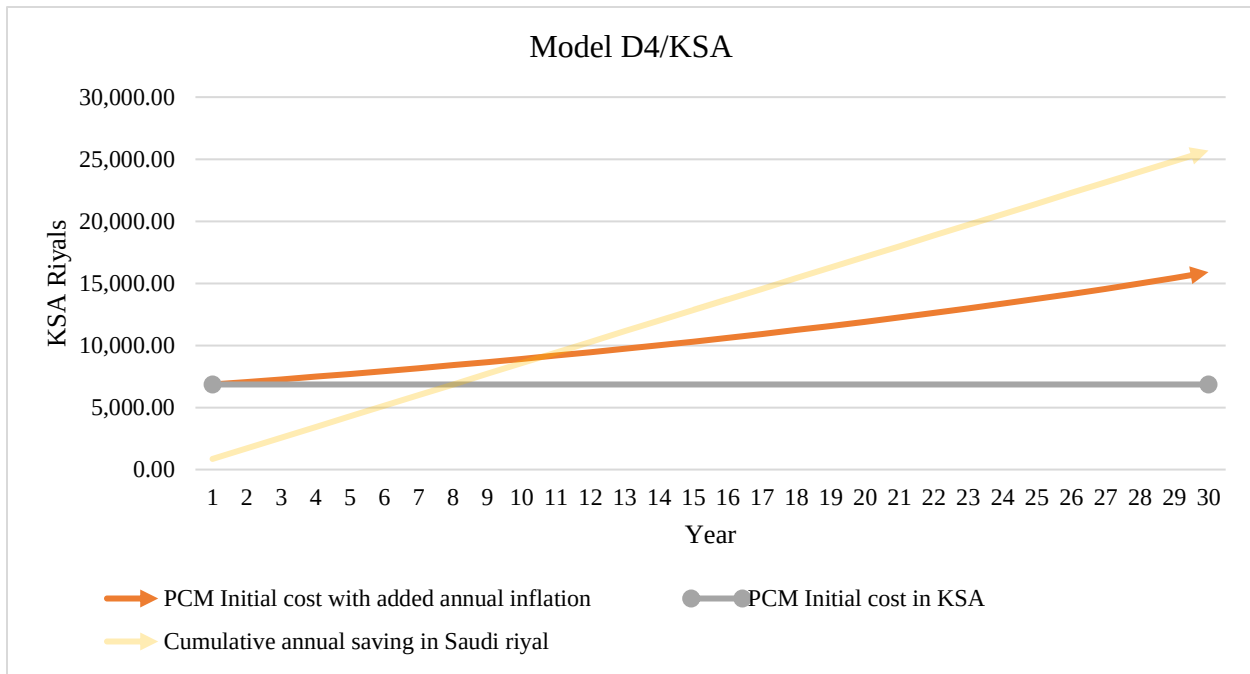


Figure 136. Model D4/KSA Proposed Pricing: 8-Year Plan Difference After the Application of Inflation Rate.

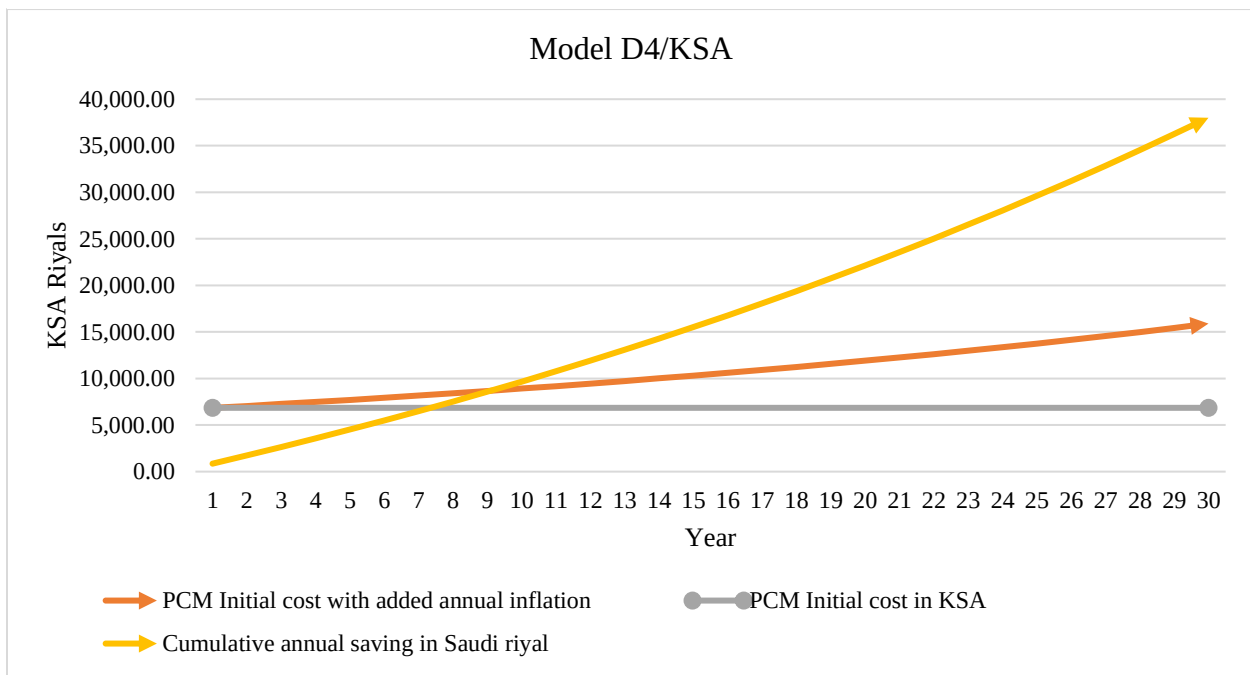


Figure 137. Model D4/KSA Proposed Pricing: 8-Year Plan Difference After the Application of Inflation & Electrical Rate.

Based on the LCCA results, the 10-year plan anticipates average savings of SAR 11,307 due to cost increases over the next 29 years. Additionally, projected energy savings presented by the light-yellow line, amount to SAR 17,132 in future passive savings (Fig. 138). The future return on investment is expected to rise from SAR 17,132 to SAR 29,424 after factoring in inflation in the electrical rate, which results in a reduced return time frame and an extended savings period (Fig. 139).

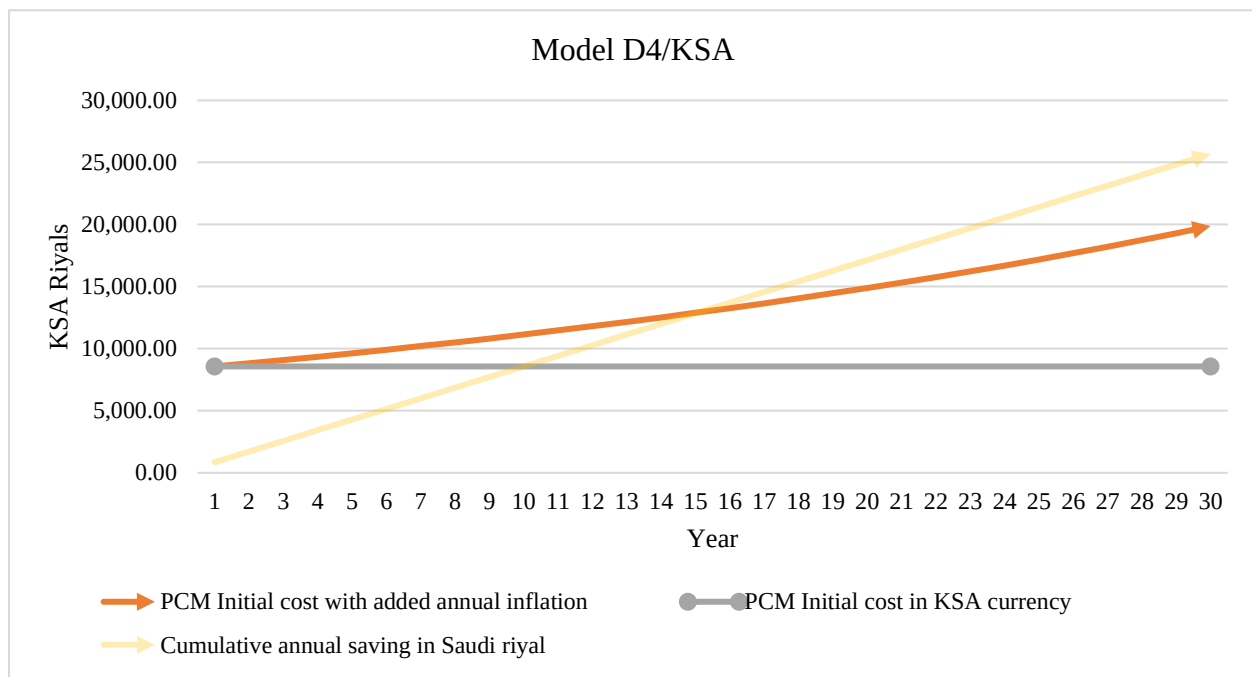


Figure 138. Model D4/KSA Proposed Pricing: 10-Year Plan Difference After the Application of Inflation Rate.

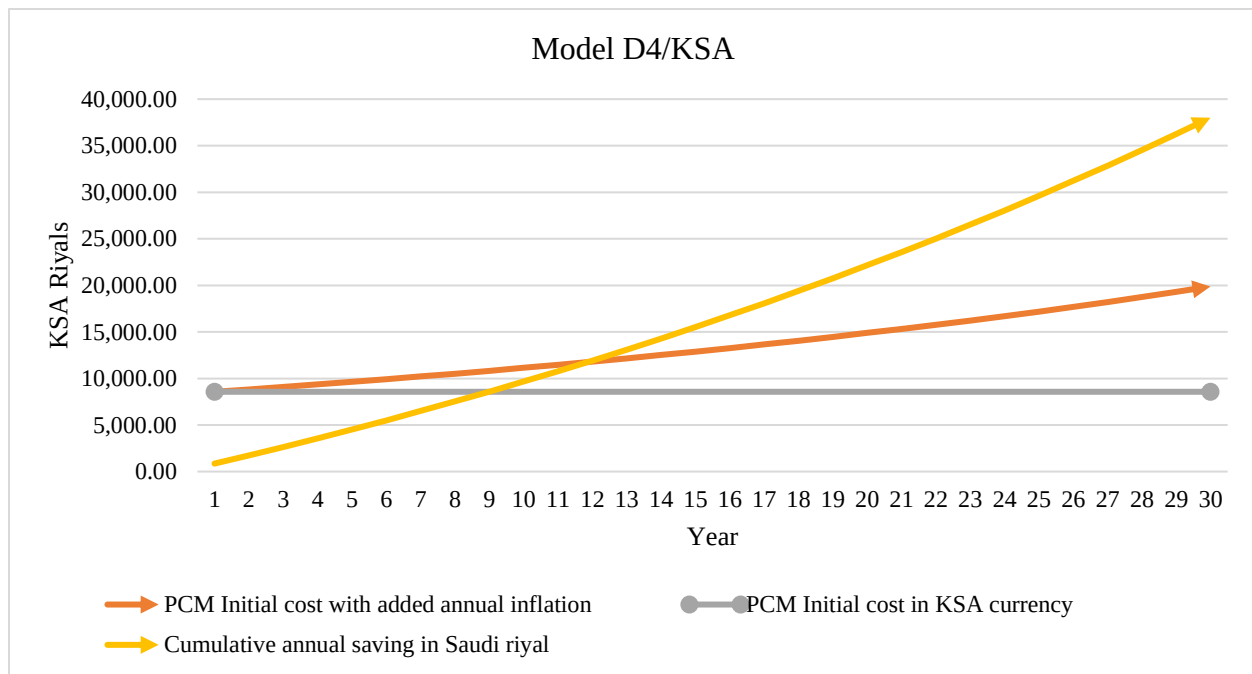


Figure 139. Model D4/KSA Proposed Pricing: 10-Year Plan Difference After the Application of Inflation & Electrical Rate.

The last two sections focus on addressing inflation in electricity rates and US inflation rates accounting for uncertainties over time. The objective was to align the model with real-world trends in inflation and electricity prices. An average annual increase of 2.87% was calculated to reflect the unpredictable nature of inflation in PCM pricing, in addition to a 2.67% annual increase in electricity rates. The impact on models, whether increasing or decreasing savings, was visually illustrated to reflect the difference between the fixed initial cost and the price increase due to inflation, along with the cumulative savings from their application.

Chapter 7: Conclusion

7.1 Research Contribution Goal

The research explored and enhanced the application of PCMs in modular housing in Riyadh, KSA. The objectives were to determine the optimal thickness and placement of PCMs, assessing their impact on thermal performance, and initial construction costs. The application of PCM is gaining attention for its benefits but the impact of the initial PCM cost compared to its energy-saving attributes has not been systematically explored. The goal is to support the decision to apply PCM in construction projects by demonstrating its proven benefits. Determining the production cost of PCMs based on their performance outcomes and ensuring they are financially viable and competitive within KSA's construction industry.

7.1.1 Optimum Thickness and Placement of PCM

Based on the results from the models in Group B, the application of PCM as a second layer from the outside did not result in substantial savings compared to the study's base case. Monthly energy consumption within this group remained consistent and showed only slight differences in energy savings across all models, as shown in Figure 140.

The application of PCM as a middle layer within the wall structure in Group C, by implementing XPS foam layers on both sides of the PCM, indicated better performance compared to Group B; however, the difference was not significant enough to fully support the application of the material. Group C results revealed only minor changes, with an unexpected pattern of fluctuating energy reductions and increased contrast with Group B. Model C1 initially revealed a reduction in cooling energy, but this trend reversed in Model C2. Increased thickness revealed

energy reduction that in turn began to recover in Models C3 and C4, both of which demonstrated greater savings than Model C2 (Fig. 141).

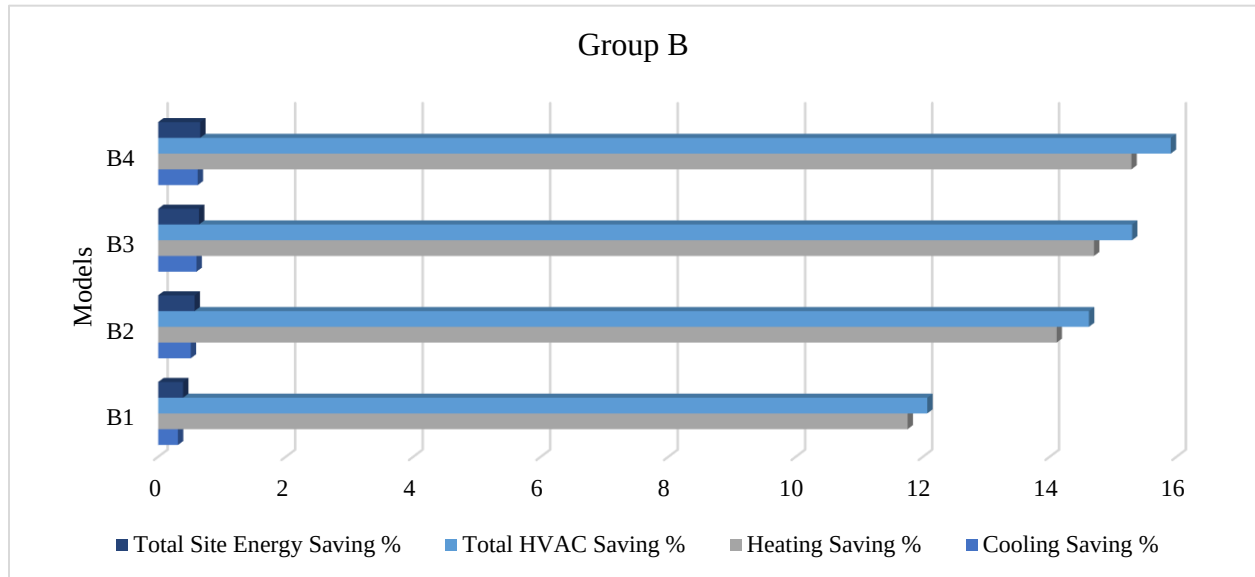


Figure 140. Savings in Energy Breakdown in Group B.

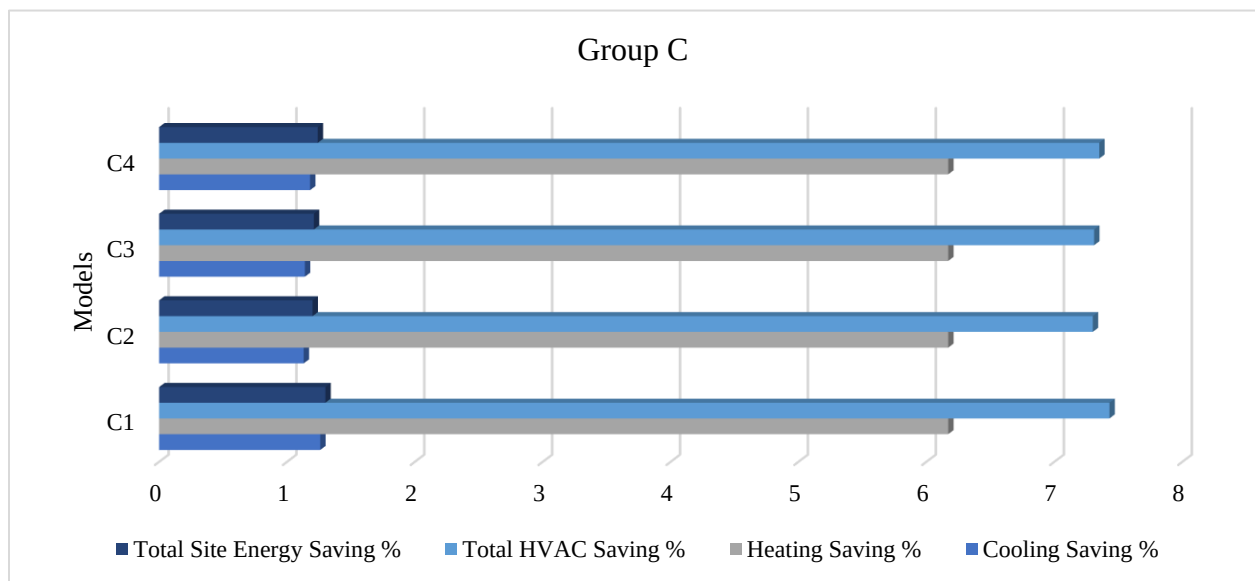


Figure 141. Savings in Energy Breakdown in Group C.

In Group D models, the PCM effectively met the expected reduction in energy consumption when was placed as the second layer from the interior. Compared to Groups B and C, these models demonstrated a significant monthly decrease in energy use. A distinct correlation emerged between thickness and energy savings, with the group’s performance demonstrating a steady increase in savings from the lowest in model D1 to the highest in model D4, where the PCM layer was thickest (Fig. 142).

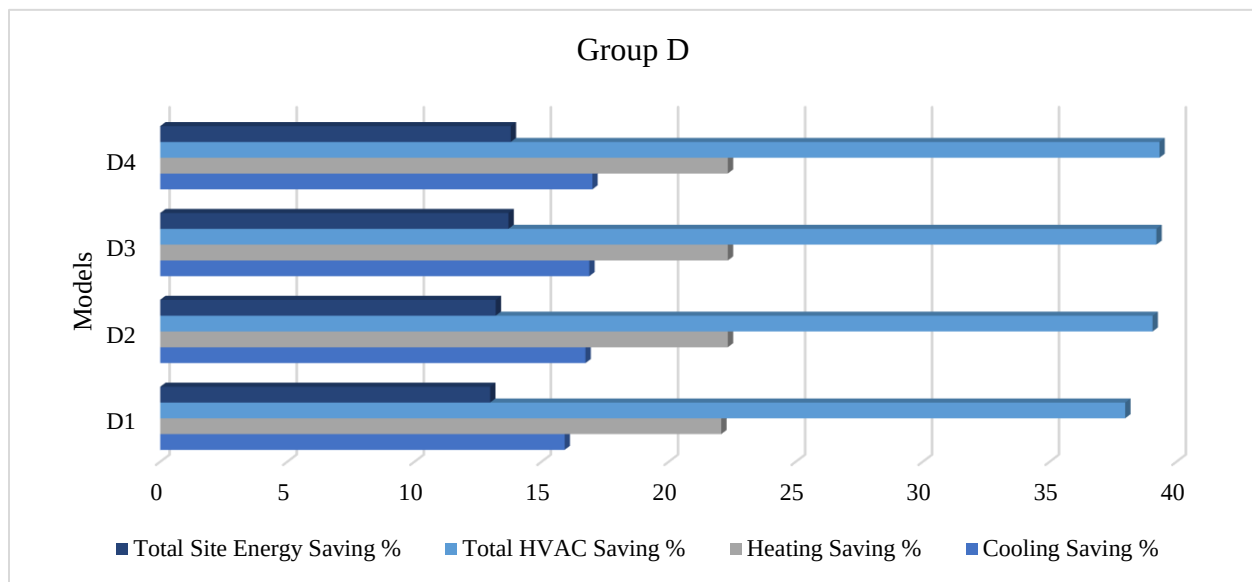


Figure 142. Savings in Energy Breakdown in Group D.

The simulation results demonstrate the impact of the PCM application on the wall’s thermal performance and highlight the variations that occurred by changing the PCM placement and thickness of the PCM. Based on the simulation results obtained from the Models in groups B, C, and D, when compared to the study base case model A with no PCM. The recommendation is to utilize PCM as the second layer from the inside with SIPs to obtain optimum performance, as in Group D with the D4 having the highest PCM thickness.

7.1.2 LCCA Analysis on Optimum PCM Model

The impact of PCM thickness and location on Models D1 and D4 was investigated via LCCA analysis. This research used an established average based on U.S. electricity rate history and pricing data to investigate the financial feasibility of using PCM in the models. Model D1, with a single layer, resulted in a relatively low initial cost under a fixed average electricity rate. In contrast, Model D4 had a higher initial cost because of its increased thickness, but it achieved a higher total site energy saving percentage of 13.79%.

D1 investments are projected to be recovered within 10 years, providing passive savings of \$15,000 over the preceding 20 years, not to exceed 30 years. In contrast, D4 offers a more favorable savings percentage due to the increased thickness of the PCM and its installation. However, the analysis demonstrates that the initial cost of D4 will be recovered after 38 years, which is considered an unacceptable timeframe.

The study explored the feasibility of applying PCM in KSA by establishing Models D1/KSA and D4/KSA. The model's inputs were adjusted to reflect the local currency and electrical rates of KSA. The LCCA model revealed a significant shift in the financial outlook when costs were converted to Saudi Riyals and KSA electricity rates were applied. The data indicated that the initial cost of Model D1/KSA could not be recovered within 30 years. While Model D4/KSA failed to recover its initial cost even after 70 years. The results from the two models showed that PCM investments in KSA are impractical under current pricing and economic conditions, highlighting the critical need for price adjustments to make PCM a viable energy-saving solution in the region.

7.1.3 Price Adjustment Proposal & Manufacturing Proposal

Suggested pricing for PCM is derived from the actual cumulative annual energy savings observed after its application. For example, if the goal is to recover the initial cost within 8 years, the study used the cumulative energy savings listed for the 8th year in the LCCA model. The model indicates a total of SAR 9,000 from the cumulative savings by the 8th year. This figure reflects the total energy savings achieved from the installation of PCM. Based on this, the proposed price was established by calculating both the installation cost and the PCM material cost per square foot, which together total SAR 6,450. This total reflects the benefits of PCM's initial cost in comparison to its annual savings over the 8-year period.

The proposed pricing is based on the LCCA analysis which is accurate to the model's performance and pricing. In the case of Model D1/KSA, for PCM to be desirable, it has to yield an investment with an 8-10-year maximum return plan. Based on the LCCA forecast, the initial cost of PCM for this project must start from a minimum range of SAR 6,450 to SAR 8,063 based on the cumulative savings gained from PCM application (Fig. 143).

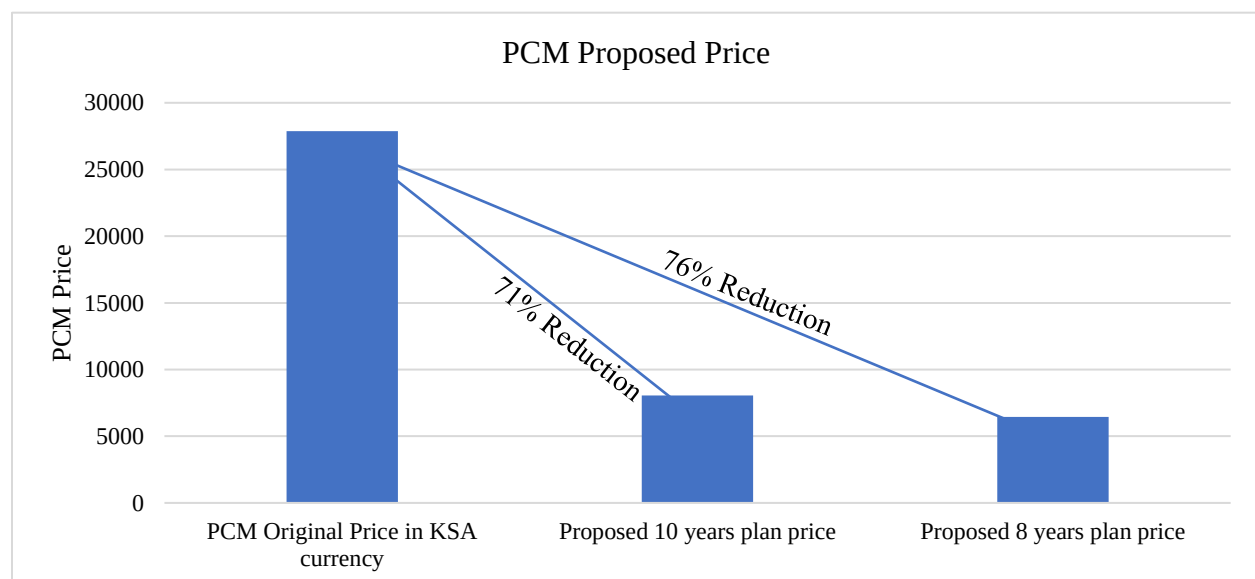


Figure 143. Model D1/KSA, PCM Proposed Pricing Reduction Percentage.

Model D4 reflects higher savings but is not an applicable choice for future investments. In this situation, a recommendation to the manufacturer would be suggested to produce the PCM panels with a thickness of 2.0 cm, which in turn will increase pricing of a single panel by 30% to cover the extra filling of PCM. However, the manufacturing adjustment on Model D4 LCCA was applied and reflected a 22-year plan to recover the initial cost.

The manufacturing proposal enhanced the savings percentage in Model D4 but still reflects an excessive initial cost. Based on the LCCA analysis forecast, Model D4, after the manufacturing proposal, demonstrates an assured price range between \$6,350 and \$7,938, based on the cumulative savings gained from the annual savings, to be desirable as a choice (Fig. 144). Meanwhile, for the Model D4/KSA price adjustment is acceptable, as pricing must be within the range of SAR 6,853 – SAR 8,566 to meet the 8-10-year investment plan (Fig. 145).

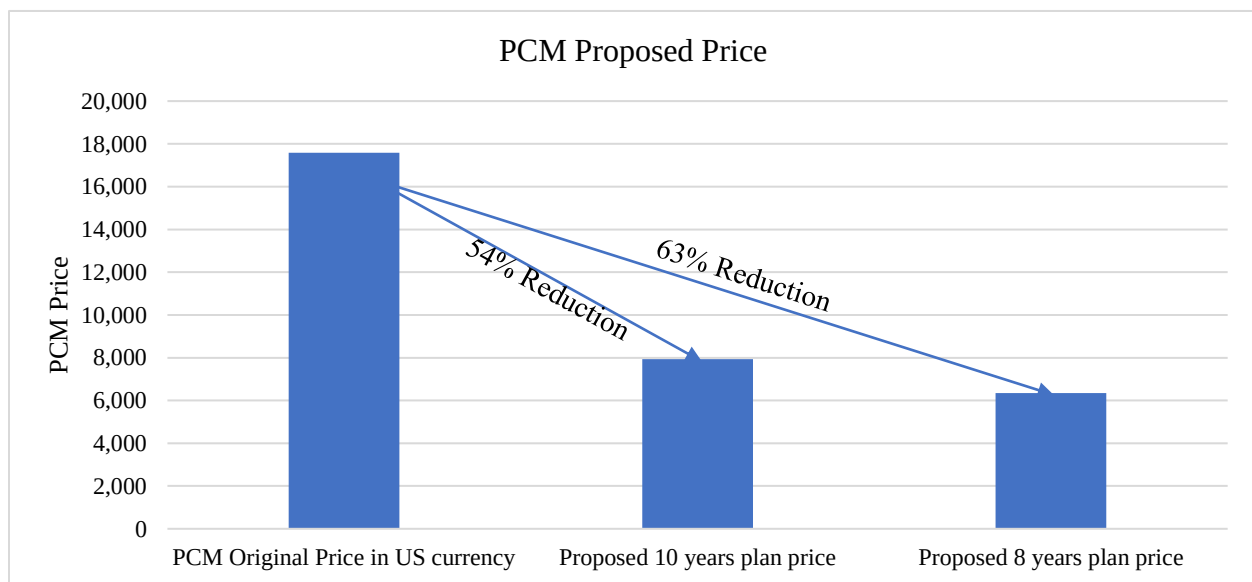


Figure 144. Model D4, PCM Proposed Pricing Reduction Percentage after Manufacturing Adjustment Proposal.

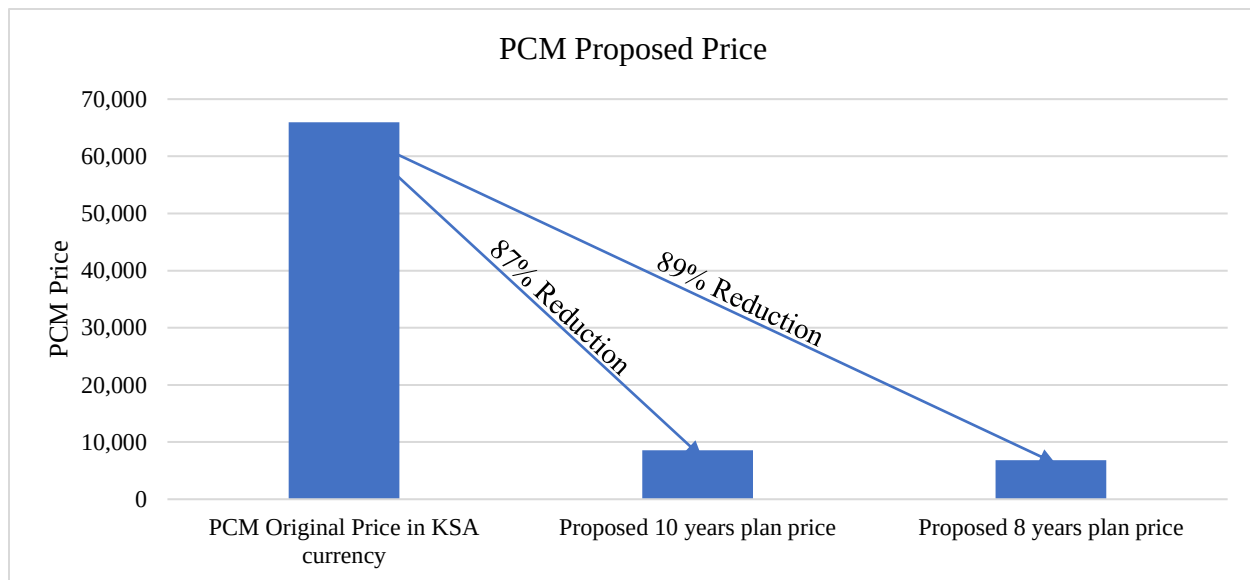


Figure 145. Model D4/KSA, PCM Proposed Pricing Reduction Percentage after Manufacturing Adjustment Proposal.

7.1.4 Electrical Rate Inflation Application

The application of the inflation rate while keeping other variables fixed is intended to demonstrate the impact of rising electrical rates and to demonstrate the benefits of PCM over time. Electricity rate baseline used is the LCCA is 0.16 SAR/kWh, which is based on the current tariff in Saudi Arabia. An annual increase of 2.67% was applied to account for projected electricity inflation over the next 30 years in the LCCA model.

In the D1 model, applying inflation to the electrical rate reduced the investment return timeframe from 10 years to 9 years and increased future savings over the next 21 years to \$26,200. However, in Models D1/KSA, although inflation had a significant impact, it still did not make the investment desirable; the return period was reduced from 35 to 25 years but remained unappealing.

While the benefits of applying inflation to the proposed pricing for Models D1/KSA were noticeable—reducing the return timeframe and increasing passive savings—the high initial cost of Model D4 meant the investment return period remained lengthy, despite a notable reduction in

return years. For Group D4, applying the electrical inflation rate to the proposed pricing models reduced the return on investment by 1 to 1.7 years and increased future savings in both the 8-year and 10-year plans.

Inflation did not significantly affect Model D4/KSA at the standard price rate. However, when applying inflation to the proposed pricing for Model D4/KSA, both investment return plans showed a reduction in the time needed to recover the initial cost—by 0.9 years in the 8-year plan and 1.4 years in the 10-year plan. Additionally, projected savings over the next 20 years increased to SAR 31K in the 8-year plan and approximately SAR 29.4K in the 10-year plan.

7.1.5 Initial Cost Inflation Rate Application

The goal of adding the inflation rate is to demonstrate its impact on initial pricing over time and the result in passive savings. Baseline cost of PCM from US suppliers was estimated at 6.3\$ per square foot, which is approximately SAR 23.8 per square foot. The study applied an annual inflation rate of 2.87% to the LCCA model to account for projected increases in both material and labor costs over time for the next 30 years. The inflation application goal is to ensure accurate long-term cost predictions for PCM implementation in modular housing.

The early application of PCM in Model D1 is projected to yield an average savings of \$9,815 over the next 30 years, along with future passive savings from PCM applications. However, Model D4 is not desirable due to its high initial cost, despite additional savings from inflation. These results underscore the importance of the proposed pricing and manufacturing adjustments, as supported by the analysis in this study.

When applying the inflation rate to the proposed pricing for Model D4/KSA and based on the LCCA analysis, the PCM-proposed pricing in the 8-year plan, with the initial cost remaining constant in the first year, resulted in an average saving of SAR 9,046 over the next 29 years. In

contrast, the 10-year plan, also based on the LCCA, shows that an increase in the initial cost over time leads to an average savings of SAR 11,307.

This study has demonstrated the outcomes of PCM application in SIPs in modular housing in KSA, Riyadh, when implementing PCM in SIPs to maximize energy performance and energy savings, as a second layer from the inside. The study established that a thickness of 0.5 cm would decrease the site's total energy by 12.98%, as in model D1, and the saving would increase to 13.79% when increasing the thickness of PCM to 2.0 cm. The selection of the thickness is dependent upon supply pricing that encourages the application of either thickness based on the proposed pricing and the adjustment of the product to be desirable for industry use.

The findings of this study can serve as a benchmark for PCM manufacturer's and contractor's pricing in construction projects. The LCCA cost proposal can be applied to assess the pricing of PCM manufactured in the KSA, thereby enabling a comparison of production costs and potential profits in the PCM market. Additionally, this approach can aid in material selection and procurement for construction projects by comparing benefits and costs, thus facilitating more informed decision-making.

7.2 Contributions to the Body of Knowledge

This research contributes to the field of sustainable construction, which aligns with the framework of Saudi Arabia's Vision 2030. The use of PCM in modular housing presents an innovative contribution by offering a practical alternative to traditional thermal mass. The study investigated PCM use by optimizing the thickness and placement of PCM, thereby reducing energy consumption and improving the thermal performance of buildings. The optimization of PCM in modular housing addresses the specific challenge of high cooling loads in Saudi Arabia.

The optimum position and thickness of PCM is one of the primary contributions of this research. The study investigated all expected placements and thicknesses, demonstrating the optimal placement of the second layer from the inside. This study provides practical guidance for architects and engineers when designing more energy-efficient buildings. Furthermore, this study quantifies the potential energy savings under the impact of PCM application and shows a reduction of the total site energy by 12.98% to 13.79% and HVAC energy consumption by 37% to 39% depending on the thickness utilized. The results confirmed the effectiveness of PCM as a sustainable construction material, providing a solid foundation for further applications in the industry.

The study also contributed to the economic feasibility discussion by including an LCCA. This analysis evaluates the cost-effectiveness of PCM in terms of the energy savings it delivers, thereby helping to establish PCM as a viable solution for the Saudi construction market. In addition, the LCCA analysis demonstrated an accurate price baseline for PCM for local production and domestic or international purchases when considered in other projects.

7.3 Research Highlights

During the research process and in addition to the main goals of the research, the results highlighted several key areas. The researcher identified new factors that could impact the results. Recommendations based on these observations were developed to enhance future building science and related fields.

7.3.1 Energy+ Highlights:

Energy+ is powerful software and the accuracy of its output depends heavily on the quality of the input provided by the user. Detailed and precise inputs are crucial for reliable predictions of building performance, energy consumption, and savings. The importance of accurate data input cannot be overstated because it directly influences the reliability of the results.

This study emphasizes the significance of correctly inputting internal workload schedules, which has an influence on the result in particular working hours. Misunderstanding these inputs can lead to inaccurate energy consumption calculations. For example, the work hours of internal loads can significantly affect cooling loads. Operation during the peak summer afternoon hours when external temperatures are highest, considerable additional energy is needed to reduce the space temperature. Inversely, running these loads during milder nighttime or winter hours can reduce heating bills due to the heat generated. Understanding and correctly applying these factors is essential for accurate simulations.

7.3.2 Results Highlight

- 1- The breakdown for the months from May to October indicates that cooling energy represents 80% of the total monthly consumption.
- 2- The simulation results indicate that the thermal performance of SIPs is generally superior to that of brick, reducing the total site energy by 9%.

- 3- SIPs exhibit high thermal performance in the hot season and low thermal performance in the cold season. In contrast to brick material, the performance of brick walls was more efficient in the cold season since it utilized the thermal mass effect, whereas its performance was weak during the hot season.
- 4- The energy breakdown shows that the SIP model utilizes more energy for cooling in the winter, which does not make sense according to the season's low-temperature degrees. SIPs have high thermal resistance, which indicates that the use of cooling is due to internal loads, which can be taken advantage of in cold climate conditions.
- 5- Internal loads and fenestration play critical roles in the heat production and heat gain of the model when using SIPs.

7.4 Future Research

The pursuit of sustainable development is a crucial aspect nationwide and for developing countries that aim to achieve a sustainable future and quality of life. KSA's Vision 2030 has an ambitious goal to reduce reliance on fossil fuels and improve sustainable construction and energy efficiency in buildings. This research explored factors that align with Vision 2030 goals by examining current practices, emerging technologies, and policy implications to provide insights into the construction industry's role in fostering a sustainable future for Saudi Arabia. According to the research findings and outcomes, there are a couple of overlapping topics that can be developed based on the research outcomes:

1. **Modular Housing Automation:** There is an urgent need for further research into the assembly, manufacturing, and automation of PCM systems, specifically for modular housing applications. Investigations should focus on optimizing production processes through automation to reduce costs, enhance precision, and improve scalability. Automated

manufacturing and assembly methods can ensure consistent quality control, streamline the integration of PCM into prefabricated modular components, and increase the efficiency of deployment.

2. **Optimization of PCM in Different Climatic Zones:** This research can be extended to other climatic zones within Saudi Arabia or other countries with similar climates. This involves testing and optimizing the PCM performance in regions with different climatic conditions.
3. **Integration of Passive Design with PCM:** Explore the integration of PCM with other renewable energy systems as the Vision 2030 target. This could involve examining the synergies between PCM and renewable energy in terms of reducing peak energy demand and improving overall building performance.
4. **User Behavior and PCM Effectiveness:** Investigating user behavior is critical for understanding the effectiveness of PCM in residential and other types of buildings. This involves examining how various occupancy patterns, thermostat settings, and lifestyle choices impact PCM performance and overall energy savings.
5. **Comparison of PCM with Other Innovative Insulation Materials:** PCM should be compared with other emerging insulation materials, such as aerogels and vacuum-insulated panels, in terms of energy efficiency, cost-effectiveness, and environmental impact. This comparison can help explore other potential sustainable construction materials in Saudi Arabia.
6. **Performance and Durability of PCM:** The study could investigate the long-term performance and durability of PCM in modular housing under Saudi Arabia's harsh climatic conditions. The research can investigate the effects of repeated thermal cycling on PCM efficiency, potential degradation over time, and maintenance requirements.

References

- Ahmad, E. H. (2002). Cost analysis and thickness optimization of thermal insulation materials used in residential buildings in Saudi Arabia. In *Proceedings of the 6th Saudi Engineering Conference, Dhahran, Saudi Arabia* (pp. 14-17).
- Al-Emad, N. H., & Rahman, I. A. (2018). Issues engulfed Saudi Arabia construction workers. *IOP Conference Series: Earth and Environmental Science*, 140, 012097.
<https://doi.org/10.1088/1755-1315/140/1/012097>
- Alaboud, M., & Gadi, M. (2019). Indoor environmental monitoring of residential buildings in Saudi Arabia, Makkah: A case study. *IOP Conference Series: Materials Science and Engineering*, 609(4), 042044. <https://doi.org/10.1088/1757-899x/609/4/042044>
- AlGhamdi, A. (2020, January 11). *Saudi Arabia Energy Report*. KAPSARC. Retrieved July 10, 2022, from <https://www.kapsarc.org/research/publications/saudi-arabia-energy-report/>
- Alghamdi. (2019, April 1). *Chapter 18: Energy*. General Authority for Statistics. Retrieved July 10, 2022, from <https://www.stats.gov.sa/en/1024>
- Al-Ghamdi, S. A., & A. Alshaibani, K. (2018). The potential of solar energy in Saudi Arabia: The Residential Sector. *Journal of Engineering and Architecture*, 6(1).
<https://doi.org/10.15640/jea.v5n2a4>
- Al-Hadhrami, L. M., & Ahmad, A. (2009). Assessment of thermal performance of different types of masonry bricks used in Saudi Arabia. *Applied Thermal Engineering*, 29(5-6), 1123–1130. <https://doi.org/10.1016/j.applthermaleng.2008.06.003>
- Al-Yasiri, Q., & Szabó, M. (2021). Incorporation of phase change materials into building envelope for thermal comfort and energy saving: A comprehensive analysis. *Journal of Building Engineering*, 36, 102122. <https://doi.org/10.1016/j.jobbe.2020.102122>

- Anas, B. (2019, August 29). *7 things I learned about “home” from talking to architects on every continent*. Apartment Therapy. Retrieved July 10, 2022, from <https://www.apartmenttherapy.com/cultural-architecture-homes-36642082>
- Barberousse, A., Franceschelli, S., & Imbert, C. (2008). Computer simulations as experiments. *Synthese*, 169(3), 557–574. <https://doi.org/10.1007/s11229-008-9430-7>
- Barreneche, C., Navarro, H., Serrano, S., Cabeza, L. F., & Fernández, A. I. (2014). New database on phase change materials for thermal energy storage in buildings to help PCM selection. *Energy Procedia*, 57, 2408–2415. <https://doi.org/10.1016/j.egypro.2014.10.249>
- Bertram, N., Fuchs, S., Mischke, J., Palter, R., Strube, G., & Woetzel, J. (2020, October 20). *Modular construction: From projects to products*. McKinsey & Company. Retrieved July 10, 2022, from <https://www.mckinsey.com/business-functions/operations/our-insights/modular-construction-from-projects-to-products>
- Cabeza, L. F., Gutierrez, A., Barreneche, C., Ushak, S., Fernández, Á. G., Inés Fernández, A., & Grágeda, M. (2015). Lithium in thermal energy storage: A state-of-the-art review. *Renewable and Sustainable Energy Reviews*, 42, 1106–1112. <https://doi.org/10.1016/j.rser.2014.10.096>
- Cartagenas, I. (2022, February 3). *Phase change material (PCM)*. Thermtest Inc. Retrieved July 10, 2022, from <https://thermtest.com/phase-change-material-pcm>
- Climate change impacts*. National Oceanic and Atmospheric Administration. (n.d.). Retrieved July 10, 2022, from <https://www.noaa.gov/education/resource-collections/climate/climate-change-impacts>

Craven, J. (2019, August 1). *'form follows function' is the most famous phrase in architecture.*

ThoughtCo. Retrieved July 10, 2022, from <https://www.thoughtco.com/form-follows-function-177237>

Creswell, J. W. (n.d.). *Research design: Qualitative, quantitative, and mixed methods*

approaches. Google Books. Retrieved July 10, 2022, from https://books.google.com/books/about/Research_Design.html?id=PViMtOnJ1LcC

Creswell, J. W., & Creswell, J. D. (2018). *Research design: Qualitative, quantitative, and mixed methods approaches*. Amazon. Retrieved July 10, 2022, from

<https://www.amazon.com/Research-Design-Qualitative-Quantitative-Approaches/dp/1506386709>

Darkin, B. (2003). International Relations and Global Climate Change Urs Luterbacher, Detlef F.

Sprinz (eds.), MIT Press, Massachusetts Institute of Technology, Cambridge, MA, 2001, 343 pp, price: £15.59, ISBN: 0-262-62149-5. *Climate Policy*, 3(2), 179–181.

[https://doi.org/10.1016/s1469-3062\(03\)00026-3](https://doi.org/10.1016/s1469-3062(03)00026-3)

De Souza, R. C. F. (2015). Case Studies as method for architectural research.

Dillinger, J. (2017, April 25). *Fossil fuel dependency by country*. WorldAtlas. Retrieved July 10,

2022, from <https://www.worldatlas.com/articles/countries-the-most-dependent-on-fossil-fuels.html>

EnergyPlus. (n.d.). Retrieved July 10, 2022, from <https://energyplus.net/>

Environmental Protection Agency. (n.d.). EPA. Retrieved July 10, 2022, from

<https://www.epa.gov/energy/electricity-customers>

Evolution of Energy Sources: The Geography of Transport Systems. The Geography of Transport Systems | The spatial organization of transportation and mobility. (2022, May 10).

Retrieved July 10, 2022, from

<https://transportgeography.org/contents/chapter4/transportation-and-energy/energy-sources-evolution/>

Espinosa Construction LLC. (n.d.). *Espinosa Construction: Building a better tomorrow*.

Retrieved October 28, 2024, from <https://espinosaconstructionllc.net/>

Felimban, A., Prieto, A., Knaack, U., Klein, T., & Qaffas, Y. (2019). Assessment of current energy consumption in residential buildings in Jeddah, Saudi Arabia. *Buildings*, 9(7), 163.

<https://doi.org/10.3390/buildings9070163>

Global Status Report for Buildings and Construction. (n.d.). Retrieved from

https://wedocs.unep.org/bitstream/handle/20.500.11822/34572/GSR_ES.pdf

Hoskin, M. (2004). Book review: The temples of Malta: Malta before history: The world's oldest freestanding stone architecture. *Journal for the History of Astronomy*, 35(4), 493–493.

<https://doi.org/10.1177/002182860403500413>

Housing program. Vision 2030. (n.d.). Retrieved July 10, 2022, from

<https://www.vision2030.gov.sa/v2030/vrps/housing/>

Humphreys, P. (1994). Numerical experimentation. *Patrick Suppes: Scientific Philosopher*, 103–121. https://doi.org/10.1007/978-94-011-0776-1_5

Humphreys, P. (2007). *Extending ourselves: Computational science, empiricism, and scientific method*. Oxford University Press.

History.com Editors. (n.d.). *Industrial Revolution*. History. Retrieved October 28, 2024, from

<https://www.history.com/topics/industrial-revolution/industrial-revolution>

Illankoon, I. M., & Tam, V. W. (2020). Life cycle costing for decision making in construction and Demolition Waste Management: A critical review. *Collaboration and Integration in*

Construction, Engineering, Management and Technology, 163–169.

https://doi.org/10.1007/978-3-030-48465-1_28

Innova Panel. (2024, October 17). *SIP installation cost estimating guide*. Retrieved from

https://innovapanel.com/building_kit-2/sip-estimating-guide/

Insolcorp. (n.d.). *Insolcorp: Advanced phase change material solutions*. Retrieved October 28, 2024, from <https://insolcorp.com/>

Jebeile, J. (2017). Computer Simulation, experiment, and novelty. *International Studies in the Philosophy of Science*, 31(4), 379–395. <https://doi.org/10.1080/02698595.2019.1565205>

Kalaiselvam, S., & Parameshwaran, R. (2014). Latent thermal energy storage. *Thermal Energy Storage Technologies for Sustainability*, 83–126. <https://doi.org/10.1016/b978-0-12-417291-3.00005-0>

Karaman, S., Karaipekli, A., Sarı, A., & Biçer, A. (2011). Polyethylene Glycol (peg)/diatomite composite as a novel form-stable phase change material for thermal energy storage. *Solar Energy Materials and Solar Cells*, 95(7), 1647–1653.

<https://doi.org/10.1016/j.solmat.2011.01.022>

LLC, B. L. S. (n.d.). *Table of contents: Input output reference - energyplus 22.1*. Big Ladder Software. Retrieved July 11, 2022, from [https://bigladdersoftware.com/epx/docs/22-](https://bigladdersoftware.com/epx/docs/22-1/input-output-reference/)

[1/input-output-reference/](https://bigladdersoftware.com/epx/docs/22-1/input-output-reference/)

Mahlia, T. M. I., Saktisahdan, T. J., Jannifar, A., Hasan, M. H., & Matseelar, H. S. C. (2014). A review of available methods and development on energy storage; technology update. *Renewable and Sustainable Energy Reviews*, 33, 532–545.

<https://doi.org/10.1016/j.rser.2014.01.068>

- Mehling, H., & Cabeza, L. F. (2008). Heat and cold storage with PCM. *Heat and Mass Transfer*.
<https://doi.org/10.1007/978-3-540-68557-9>
- Modular construction, advantages and challenges*. Real Projectives. (2021, June 29). Retrieved July 11, 2022, from <https://www.realprojectives.com/the-advantages-and-challenges-of-modular-construction/>
- Muruganantham, K., Phelan, P., Horwath, P., Ludlam, D., & McDonald, T. (2010). Experimental investigation of a bio-based phase change material to improve building energy performance. *ASME 2010 4th International Conference on Energy Sustainability, Volume 1*. <https://doi.org/10.1115/es2010-90035>
- Nikzad, R., & Sedigh, G. (2017). Greenhouse gas emissions and Green Technologies in Canada. *Environmental Development*, 24, 99–108. <https://doi.org/10.1016/j.envdev.2017.01.001>
- Ogden, R., Lawson, R. M., & Goodier, C. I. (2014). *Design in modular construction*. CRC Press.
- Products & pricing*. ACME Panel Structural Insulated Panels - SIPs. (2021, January 6).
<https://acmepanel.com/products-pricing/>
- Ritchie, H., Roser, M., & Rosado, P. (2020, May 11). *CO2 emissions*. Our World in Data.
 Retrieved July 10, 2022, from <https://ourworldindata.org/co2-emissions>
- Sadineni, S. B., Madala, S., & Boehm, R. F. (2011). Passive Building Energy Savings: A review of Building Envelope Components. *Renewable and Sustainable Energy Reviews*, 15(8), 3617–3631. <https://doi.org/10.1016/j.rser.2011.07.014>
- Sari, A. (2014). Composites of polyethylene glycol (PEG600) with gypsum and natural clay as new kinds of building pcms for low temperature-thermal energy storage. *Energy and Buildings*, 69, 184–192. <https://doi.org/10.1016/j.enbuild.2013.10.034>

- Saudi Arabia: Electricity consumption by sector 2020*. Statista. (2022, February 14). Retrieved July 10, 2022, from <https://www.statista.com/statistics/975288/saudi-arabia-electricity-consumption-by-sector/>
- ScienceDaily. (n.d.). *Earth's atmosphere*. ScienceDaily. Retrieved July 10, 2022, from https://www.sciencedaily.com/terms/earth%27s_atmosphere.htm
- SEEC. (n.d.). Retrieved July 10, 2022, from <https://www.seec.gov.sa/ar/>
- Shilei, L., Neng, Z., & Guohui, F. (2006). Impact of phase change wall room on indoor thermal environment in Winter. *Energy and Buildings*, 38(1), 18–24.
<https://doi.org/10.1016/j.enbuild.2005.02.007>
- Soria López, F. J. (2006). Architecture and nature at the end of the 20th century: Towards a dialogical approach for sustainable design in Architecture. *Eco-Architecture: Harmonisation between Architecture and Nature*. <https://doi.org/10.2495/arc060031>
- Solar Reviews. (2024, October 20). *Average electricity cost increase per year*. Retrieved October 28, 2024, from <https://www.solarreviews.com/blog/average-electricity-cost-increase-per-year>
- U.S. Energy Information Administration - EIA - independent statistics and analysis. International - U.S. Energy Information Administration (EIA). (n.d.). Retrieved July 10, 2022, from <https://www.eia.gov/international/analysis/country/SAU>
- Unfccc.int. (n.d.). Retrieved July 10, 2022, from <https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement>
- United Nations. (n.d.). *What is climate change?* United Nations. Retrieved July 10, 2022, from <https://www.un.org/en/climatechange/what-is-climate-change>

- US Inflation Calculator. (n.d.). *Current inflation rates*. Retrieved October 28, 2024, from <https://www.usinflationcalculator.com/inflation/current-inflation-rates/>
- Vitruvius's theories of beauty - vll-minos.bl.uk. (n.d.). Retrieved July 10, 2022, from <http://vll-minos.bl.uk/learning/cult/bodies/vitruvius/proportion.html>
- Wertz, F. J. (2011). *Five ways of doing qualitative analysis: Phenomenological Psychology, grounded theory, discourse analysis, Narrative Research, and Intuitive Inquiry*. Guilford Press.
- Westgate, R. (2018). A survey of approaches to Greek and roman art - (c.) Marconi (ed.) The Oxford Handbook of Greek and Roman art and architecture. pp. XVIII + 710, ills, maps. New York: Oxford University Press, 2015. cased, £120, US\$160. ISBN: 978-0-19-978330-4. *The Classical Review*, 68(1), 200–202. <https://doi.org/10.1017/s0009840x17001615>
- Wijesuriya, S., Tabares-Velasco, P. C., Biswas, K., & Heim, D. (2020). Empirical validation and comparison of PCM modeling algorithms commonly used in building energy and Hygrothermal Software. *Building and Environment*, 173, 106750. <https://doi.org/10.1016/j.buildenv.2020.106750>
- Yin, R. K., & Campbell, D. T. (2018). *Case study research and applications: Design and methods*. Amazon. Retrieved July 10, 2022, from <https://www.amazon.com/Case-Study-Research-Methods-Applied/dp/1452242569>
- Zhou, Z., Zhang, Z., Zuo, J., Huang, K., & Zhang, L. (2015). Phase change materials for solar thermal energy storage in residential buildings in Cold Climate. *Renewable and Sustainable Energy Reviews*, 48, 692–703. <https://doi.org/10.1016/j.rser.2015.04.048>
- Zhuang, C.-long, Deng, A.-zhong, Chen, Y., Li, S.-bo, Zhang, H.-yu, & Fan, G.-zhi. (2010). Validation of veracity on simulating the indoor temperature in PCM light weight building

by Energyplus. *Lecture Notes in Computer Science*, 486–496. https://doi.org/10.1007/978-3-642-15621-2_53