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Passive Building Energy Saving: Building Envelope Retrofitting Measures to Reduce Cooling Requirements for a Residential Building in an Arid Climate

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Abstract: In arid climates, a significant portion of the urban peak energy demand is dedicated to cooling and air-conditioning during the summer. The rapid urbanization rates in developing countries, particularly in the Gulf Cooperation Council (GCC), have intensified the pressure on energy resources to meet the indoor comfort needs of residents. As a result, there has been a substantial increase in energy demand, with a 2.3% rise recorded in 2018. Electricity consumption in residential buildings accounted for over 48.6% of the total electricity consumption. The choice of building fabrics used in a residential building can significantly impact the building's passive performance and carbon footprint. This study aimed to enhance our understanding of how specific fabric details influence cooling energy usage in arid climates. To achieve this, a validation simulation model was initially created as a base case for a residential housing typology in Al Ain, UAE. This was followed by a parametric energy evaluation of various building envelope features. The evaluation was based on the reduction of yearly cooling load energy. The simulation results indicate that incorporating 50 mm of expanded polystyrene insulation into the outside walls significantly reduced energy consumption for cooling requirements in the arid UAE climate. Furthermore, no substantial difference was observed in the various roofing choices, including cool and green roofs, gravels, and sand roofs. Additionally, we concluded that the total solar energy transmittance (g-value) of windows played a more significant role than thermal transmittance (U-value) in reducing solar heat gain within the spaces. These findings should guide strategic decisions on building envelope upgrading for sustainable societies.

Keywords: building fabric; arid climate; housing; cooling energy; insulation thickness

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1. Introduction

Buildings account for over 40% of primary energy use and the respective emission of greenhouse gases [1]. Increased energy usage can be attributed to factors such as larger populations, expanded housing supply, improved living standards, and the urban heat island effect. Consequently, this has led to a significant rise in energy demand, with a 2.3% increase in 2018 alone [2]. Of this, a substantial amount is used by heating, ventilation, and air conditioning (HVAC) systems, which account for about 20% of total energy usage [3]. In arid regions, however, air conditioning alone can account for more than 60% of energy use [4–6]. As such, a focus on lower cooling loads is essential in these dry areas to reduce the functioning costs of buildings via energy-efficient designs and practices [7,8], producing more energy-efficient buildings using passive or active approaches. The former refers to improvements made to building envelope components, while the latter involves enhancements to electrical lighting, HVAC systems, and other active components. The latter has more recently been the subject of renewed examination [9,10].

A building envelope comprises the roof, windows, and walls as the features which separate the outside from the inside. Together, they manage the internal space, temperature, and noise with regard to the external climate without sacrificing the aesthetic aspects of the building. The envelope serves as a physical barrier between the interior and exterior environments, providing protection, insulation, and energy efficiency. While heat is pushed through the envelope, radiative heat is exchanged with external planes or directly lost via air exchange (for example, by leaking or ventilating), thereby affecting the energy consumption of a building [11]. Optimizing the building envelope is crucial to minimize energy usage in hot, arid climates, where cooling demands are high. Studies have demonstrated that building envelope retrofitting measures, such as adding insulation to walls or roofs, can significantly reduce cooling energy consumption [12,13]. Additionally, retrofitting windows with low-emissivity coatings or shading devices can minimize solar heat gain and further contribute to energy efficiency [14]. In one study employing a well-designed building envelope, as much as a 20–50% decrease in total energy use was found to be possible [15], while an earlier study in Abu Dhabi found that the building envelope was responsible for 30% of the entire cooling load [16]. As a result, building envelope retrofitting is a key strategy for achieving sustainability by reducing worldwide energy usage, as outlined in Directive 2012/27/EU [17]. Nevertheless, while energy-efficient strategies may be widely thought of as the cheapest means of enabling a secure supply of energy and lowering greenhouse gas emissions [18], it appears that both designers and homeowners lack sufficient knowledge of the optimal technology for a building envelope and its practicability [19]. Furthermore, most current research on building envelopes has focused on climates in tropic, subtropic, and temperate zones (in descending order of occurrence) [20]. With such a lack of research centered on hot, dry climates, it becomes highly relevant to expand our understanding of how suitable building envelope design impacts residences in such climates.

In this context, the study had two aims: first, to determine how effective the various building envelope features are in a hot, arid climate, and second, to determine the maximum energy reduction achieved by incorporating various building envelope design cases, including roofs, walls, windows, and floors, for a typical residential house located in the dry climate of Al Ain as representative of the main case.

2. Review of Recent Studies

Three commonly used methods for estimating building energy consumption and thermal performance are mathematical analysis, experimental testing, and numerical modeling [21]. The first method is complex and often relies on simplifying assumptions to make the calculations more manageable. However, these simplifications may not accurately represent the complex and dynamic nature of heat transfer in real-world buildings. As a result, the analysis may overlook certain factors or interactions that could impact heat transfer [20]. The next method uses scaled models to control the building's thermal functioning, which is often impractical when considering multiple design scenarios [20,22]. As a result, the third method, numerical modeling, is preferred because it can address these limitations by providing a more accurate representation of heat transfer in buildings compared to simplified mathematical models. It can account for complex geometries, material properties, and boundary conditions with greater precision, leading to more reliable results [23]. Accordingly, and considering the limited application to the Middle East and the Gulf Cooperation Council (GCC) region [5,24,25], this section contains a critical review of recent studies that specifically focused on energy efficiency in buildings within the GCC. The review includes studies conducted in the past decade that utilize dynamic energy modeling techniques in line with widely recognized sustainable building codes.

The first study under consideration is from 2008 [26], in which Radhi analyzed the impact of various energy efficiency measures on an office building in Bahrain. These measures encompassed thermal insulation for walls and roofs, low emissivity glazing, energy-efficient systems and appliances like daylight sensors, and improved energy-saving equipment. Additionally, different cooling setpoints were examined. The implementation of these measures resulted in a significant 42% reduction in energy consumption. In another study conducted in 2009, Radhi [27] examined the effectiveness of thermal insulation in reducing energy consumption and carbon emissions in commercial and residential buildings in Bahrain. The study specifically analyzed the impact of different insulation levels, glazing types, and window-to-wall ratios on thermal comfort and overall energy consumption. The findings indicated that improving the building envelope alone did not achieve a 40% reduction in energy use and carbon emissions [27]. However, it is worth noting that these studies are relatively outdated and do not consider the most recent techniques, such as cool roofs or advanced insulation materials. Additionally, these studies focus more on early design decisions rather than retrofitting the building envelope.

Another relevant study was conducted by Taleb and Sharples [28], who focused on the hot, arid climate of Saudi Arabia. They found that implementing measures such as enhancing insulation of external walls and roofs, as well as using double-glazed windows with appropriate shading devices, could lead to a significant reduction of 32.4% in annual electricity consumption for residential buildings [28]. In the United Arab Emirates, Taleb [29] conducted a dynamic energy simulation on a residential villa in Dubai, assessing eight different passive cooling strategies, including a type of insulation, double glazing, and natural ventilation, which is not easy to apply due to the dust and noise. The study reported a 23.6% reduction in annual energy use. Similarly, in Saudi Arabia, Alaidroos and Krarti [30] examined the impact of the building envelope on energy savings in residential buildings across different cities in the country. They found that energy savings of 22.7% to 39.5% could be achieved, depending on the context and climate of the city. However, the case study was a conceptual house, and only sensitivity analysis was performed, omitting an actual validation of the simulation outcomes. In Qatar, Kharseh and Al-Khawaja [31] investigated five different energy retrofitting methods for building envelopes and their effects on cooling loads in a residential building. Their study showed potential cooling energy reductions of 53%. However, only the U-value of the external shell was considered, there was no variety in the roof types investigated, and the simulation outcomes of the base case were not validated. A similar study conducted in Kuwait by Ameer and Krarti [32] explored the impact of Kuwaiti residential building energy codes and found substantial reductions in electricity bills when the energy codes were applied. Only the existing building energy conservation code of practice was applied, and different scenarios were not examined.

Another interesting study by Wahl [33] in Saudi Arabia evaluated the energy savings achievable by adapting the building envelope using different energy efficiency measures. Energy simulations on a two-story residential building indicated that the best energy savings (21–27%) were achieved by changing the window type from single clear glass to double glass with a reflective surface. Other energy savings were gained by adding insulation to uninsulated roofs (23% total energy saving), enhancing thermal insulation of external walls (11–21%), and installing fixed shades dimensioned for the peak cooling load (8–13%). In another study in Saudi Arabia, Almushaikah and Almasri [34] assessed various energy-efficient measures in the residential sector. The results indicated that these measures led to energy consumption reductions of 27–29% for walls, 13–14% for roofs, and 6% for windows. It is worth noting that these findings differ from those of Wahl [33] regarding windows and roofs despite both studies being conducted in the same climate.

A more recent study conducted in 2021 utilized parametric energy simulations to assess the effectiveness of various energy efficiency measures in reducing annual energy consumption and carbon emissions in a residential villa. The study focused on the application of different GCC energy efficiency measures in combination with Abu Dhabi's ESTIDAMA 1 code. The most significant findings were energy savings of 24.4% and a 26.3% reduction in carbon emissions. However, the study did not consider different U-values or roofing materials [5].

To summarize, the aforementioned reviews present diverse findings regarding the potential for energy savings through the implementation of passive energy efficiency design in the arid climate locations of the GCC. The literature analysis also revealed a significant gap in the investigation of building envelopes for energy efficiency measures implemented in the UAE, despite the country having one of the highest energy consumption rates compared to similar countries in the region [35]. This report emphasizes that the UAE's high per capita energy consumption is driven by factors such as rapid urbanization, population growth, and energy-intensive industries. Additionally, the hot climate in the UAE necessitates extensive use of cooling systems, further contributing to the overall energy consumption. After conducting an extensive literature review of over 100 studies on building performance from 2001 to 2017, it was observed that most recent studies primarily focused on tropical, subtropical, and temperate climates, with hot, dry climates receiving limited attention (Figure 1) [20]. Therefore, it is crucial to gain a deeper understanding of the impact of implementing energy efficiency measures, such as passive building energy saving and building envelope retrofitting, specifically in residential buildings within hot, dry climates like the UAE's, to promote sustainability in cities.

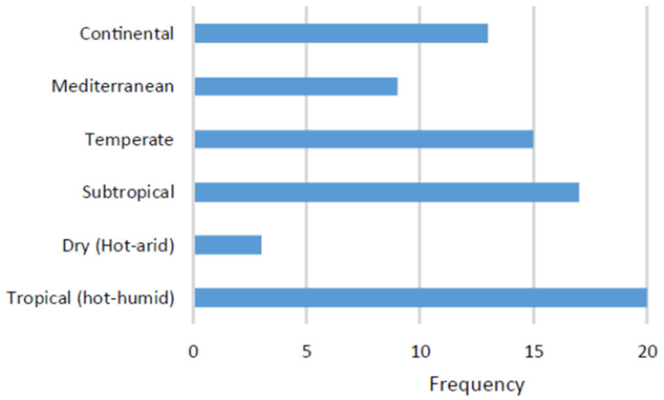


Figure 1. Distribution of studies according to Koppen's climate classification [20].

3. Methods

The study examined how different components of building envelopes, such as roofs, walls, windows, and floors, can improve energy savings for residential buildings located in arid climates. According to [36,37], creating and calibrating a suitable physical model and then iteratively adjusting variables using numerical methods can establish the relationship between the building envelope construct and how much energy is consumed. This approach generates better results in terms of practicality, accuracy, and insight compared to the other two methods mentioned previously [21]. Additionally, it allows for parametric analysis of various design scenarios, considering different levels of complexity. Therefore, dynamic building energy simulation is utilized in this study to measure the savings in energy from upgrades in the building envelope. The suggested approach was created based on the following:

1. Identifying the representative residential building typology and features via a review of the literature to include the broader details of building construction, equipment, and dimensions;
2. Creating a dynamic energy model to validate the base case;
3. Developing a parametric energy evaluation for various building envelope features on the basis of the yearly cooling load energy reduction.

3.1. Dynamic Energy Modeling Setups and Choice of Software

Various studies have assessed how simulation tools can be used to determine a building's energy and thermal functioning [38,39]. Able to handle intricate thermal modeling, the DesignBuilder version 7.0 tool has been assessed in research with comparable goals to the present study [40–42]. In alignment with the DesignBuilder manual, the necessary data were determined for the location, weather file, and the building's geometry, as well as its construction materials, HVAC system, operational details, and internal load. These data were then input to form a dynamic energy simulation model by which the base case could be validated in advance of the various building envelope scenarios under investigation.

3.2. Building Model and Climate—The Base Model

The base case in the study is a prototype apartment unit in Al Ain, a city in Abu Dhabi, UAE (24.1302° N, 55.8023° E). It is classed as a hot, dry climate area 1B by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) standards [43] and labeled as BWh with the Koppen–Geiger climate classification, standing for a hot, desert climate [44], and 0B as per the ASHRAE Standards (2009). Air temperature has a high of 35.8–43.3 °C and a low of 21.7–28.9 °C in summer, while in winter, the high varies from 23.9–26.5 °C and the low from 11.3–17.1 °C, as presented in Figure 2. The city's altitude is 310.98 m from the mean sea level, with a humidity of 21–51%.

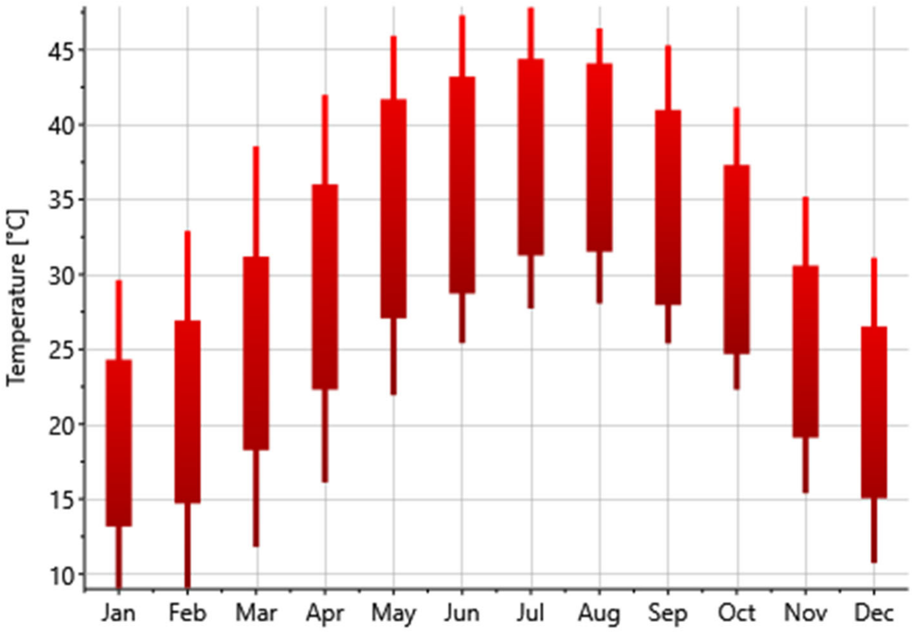


Figure 2. The average air temperature is derived from the Energy Plus Weather file for the Al Ain International Airport weather station (no. 412180).

The case study is a semi-detached two-bedroom apartment on the top floor of a two-story building (Figure 3). Each floor has two apartments, each of which is 150 m^2. Each apartment is equipped with air conditioning in three areas: the bedrooms, sitting room, and kitchen, as well as in the corridors and bathroom. The case study building was selected due to the availability of data such as drawings, materials, properties, operational details, and energy consumption levels. Having these helped to generate more accurate findings, both for this validation and for future assessments. Table 1 presents the data needed for the dynamic energy simulation, such as the location, weather, form, construction materials, HVAC system, internal load, and operational functioning. These data were utilized to build the dynamic energy simulation model for the base case (Figure 4) and the other scenarios. In this building, there is no heating system, but the air-conditioning (AC) is maintained at 24 °C. Lighting density is 5 W/m^2 for operational hours, which are weekdays from 08:00 until 16:00 when the family is at work or school and only the housemaid is at home, leading to an occupancy load of just 20% but rising to 100% when the entire family is present, such as at weekends. We assumed an occupancy density of five persons and an infiltration rate of 0.25 air changes per hour (ACH). Ventilation rates are in accordance with the available data from the Chartered Institution of Building Services Engineers (CIBSE) Guide A for the range of space types [45]. The sitting room and bedrooms were assumed to be 1 ACH, while the bathroom was 15 l/s, the kitchen 16 l/s, and the toilets 5 ACH. Concerning internal gain, a lighting density of 10 W/m^2 and equipment load of 10 W/m^2 were set. An AC system with a seasonal energy efficiency score of 2.5 was used, with a cooling thermostat setpoint of 24 °C in the occupied spaces. The basic construction technique used is Modern Methods of Construction (MMC), which involves the use of Light Gauge Steel (LGS) full system. (Figure 5). Finally, Table 2 presents the tested design parameters, including the different building envelope items. Regarding the roof retrofit technologies, the analysis includes a high albedo-coated roof known as a 'cool roof', green roofs, and light-colored gravel assembly. For the wall, five wall thicknesses were analyzed, ranging from 20 to 150 mm, in addition to three insulation thickness scenarios related to the internal floor of 20 mm, 50 mm, and 70 mm. There were also four window schemes with different U-values and g-factors. The U-value (also known as the thermal transmittance) is a measure of how well a building element (such as a window or wall) conducts heat. It is typically expressed in units of watts per square meter per degree Celsius (W/m^2·°C). The mathematical expression for the U-factor can be calculated as follows:

$$\text{U-factor} = (1/\text{R\_total}) \tag{1}$$

where R_total is the total thermal resistance of the building element, considering the resistance of each layer (such as glass, air gaps, and frames) that makes up the element. The g-factor (also known as the solar heat gain coefficient or shading coefficient) is a measure of how much solar radiation is transmitted through a window. It represents the fraction of solar heat gain that is transmitted through the window compared to the total incident solar radiation. The g-factor is dimensionless and typically ranges from 0 to 1, with a lower value indicating less solar heat gain. The mathematical expression for the g-factor can be calculated as follows:

$$\text{g-factor} = (\text{q\_transmitted}/\text{q\_incident}) \tag{2}$$

where q_transmitted is the solar heat gain transmitted through the window and q_incident is the incident solar radiation on the window.

Table 1. Modeling input for the properties of the building.

Design Element	UAE, Abu Dhabi ESTIDAMA 1 Pearl Compliance [46]
Exterior Walls	Massive wall U = 0.30 W/m^2-K
Roof	Insulation entirely above deck U = 0.20 W/m^2-K
Floor	Massive floor U = 1.65 W/m^2-K
Glazing	Double coated 6/8/6 (SHGC 0.31) U = 3.1 W/m^2-K
Occupancy density	Five occupants
System type	Constant Volume DX
Thermostat setting	24 °C for cooling (no heating is provided)
Cooling system seasonal Coefficient of Performance (CoP)	3.2
Infiltration	3.64 l/s/m^2 of exterior surface area

Figure 3. The case study residential unit.

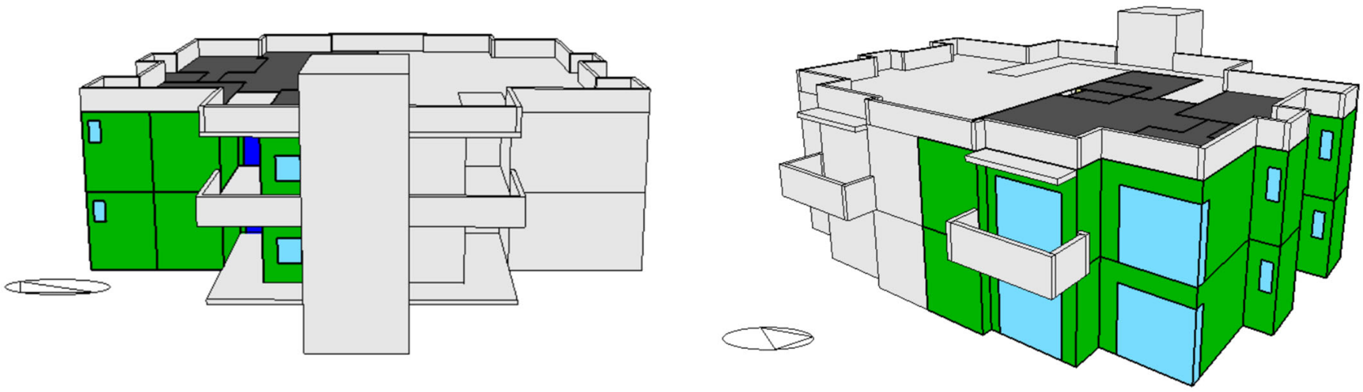
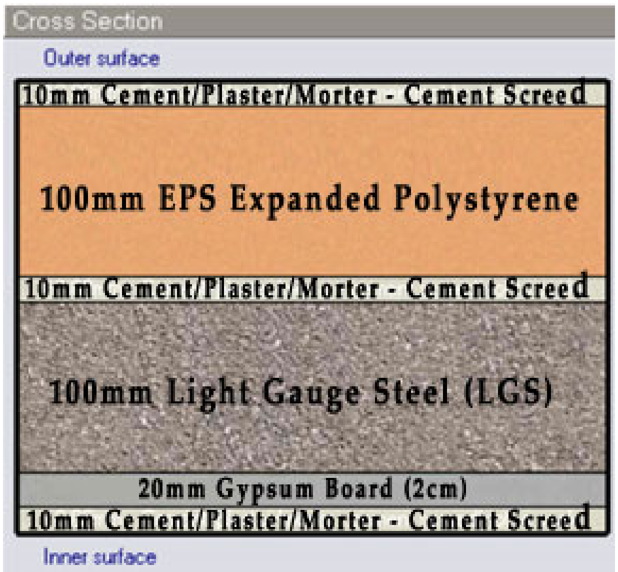


Figure 4. DesignBuilder building model for a typical semi-detached apartment case study. The north arrow on the ground shows the orientation view of the model.



Inner surface	
Convective heat transfer coefficient (W/m²-K)	2.152
Radiative heat transfer coefficient (W/m²-K)	5.540
Surface resistance (m²-K/W)	0.130
Outer surface	
Convective heat transfer coefficient (W/m²-K)	19.870
Radiative heat transfer coefficient (W/m²-K)	5.130
Surface resistance (m²-K/W)	0.040
No Bridging	
U-Value surface to surface (W/m²-K)	0.207
R-Value (m²-K/W)	4.998
U-Value (W/m²-K)	**0.200**
With Bridging (BS EN SIO 6946)	
Thickness (m)	0.250
Km-internal heat capacity (KJ/m²-K)	36.60
Upper resistance limit (m²-K/W)	4.998
Lower resistance limit (m²-K/W)	4.998
U-Value surface to surface (W/m²-K)	0.207
R-Value (m²-K/W)	4.998
U-Value (W/m²-K)	**0.200**

Figure 5. Detailed section of the Light Gauge Steel (LGS) and the calculated U-value.

Table 2. Design scenarios under analysis.

Building Feature	Modeling Scenario					
Roof	Base case	Add insulation		Cool roof	Gravel assembly	Green roof
Wall	Base case	Five insulation thickness scenarios				
	No insulation	20 mm	50 mm	70 mm	100 mm	150 mm
Floor	Base case	Three insulation thickness scenarios				
	No Insulation	20 mm		50 mm	70 mm	
Window	Base case	Four schemes with different U- and g-values				
	U value 3.1, g value 0.4	U value 3.1, g value 0.2		U value 2, g value 0.5	U value 1.6, g value 0.4	U value 1.0, g value 0.4

3.3. Database Preparation for the Tested Roof Configurations

To explore the possible advantages of using different roofing types in a hot, arid climate, a database for the examined roofs was prepared, as presented in Tables 3 and 4, including cool roofs, light-colored gravel assembly, and green roofing. The findings were then compared with uninsulated and insulated roof configurations and the base case.

Table 3. The chosen cool roof design configurations.

	Cool Roof			Gravel Assembly	
	Maker A	**Maker B**	**Maker C**	**Coarse**	**Sand**
Material	SBS with polyester reinforcement	SBS with polyester reinforcement	APP with polyester reinforcement	Grain size (8–22.4 mm)	Grain size (0–4 mm)
Thickness	4 mm	4 mm	4 mm	2 cm	2 cm
Reflectance	0.78	0.83	0.72	0.36	0.44
Emissivity	0.89	0.91	0.92	0.56	0.64

Table 4. Extensive green roof model parameters.

Properties	Value
Thermal Conductivity (W/(m_K))	0.3
Height of Plants (m)	0.3
Leaf Area Index (LAI)	5
Leaf Reflectivity	0.4
Leaf Emissivity	0.95
Minimum Stomata Resistance (s/m)	50
Maximum Volumetric Moisture Content at Saturation	0.5
Minimum Residual Volumetric Moisture Content	0.2

Cool roofs have greater reflectivity and lower absorptance than conventional roofs. The most common types of cool roofs are those with reflective granules or coatings or layers of thermoplastic membranes. For this reason, three cool roof products were selected from various manufacturers, and their specifications are presented in Table 3. Bitumen with added plastic or rubber and reflective granules are typical types of cool roof on the market. Plastic blend bitumen formed as atactic polypropylene (APP) is better for small real-world applications because it melts more easily. In contrast, bitumen modified with synthetic rubber via the addition of styrene–butadiene–styrene (SBS) is more flexible and better able to cope with greater wind stress and fluctuations in temperature [47].

The reflectiveness of light-colored gravel is influenced by the size of its grains. Pisello et al. [48] conducted laboratory and field experiments to measure the optical performance of coarse and fine-grained gravel for building applications. They found that the average monthly reflectance of sand samples (0–4 mm) was 44%, while gravel with larger grain sizes (8–22.4 mm) had a reflectance of approximately 36%. Interestingly, the laboratory data showed a higher reflectance value of 62% for sand. Table 3 provides the parameters of the gravel assembly, including the two scenarios that were tested.

The green roof is an additional alternative for two-floor residences. In general, there are two kinds—extensive and intensive—and we tested the former because of its capacity for being retrofitted to pre-existing structures with hardly any or no extra structural support. This kind is more suited to new constructions. The green roof model's features are shown in Table 4. Overall, these types of roofs were selected as they offer sustainable solutions in construction and buildings by promoting energy efficiency, mitigating the urban heat island effect, managing stormwater, enhancing biodiversity, and improving air quality [49–51].

4. Results and Discussion

We assessed the variations with the same base model validation parameters of weather file, location, geometry, orientation, and occupation schedule, as shown in Table 2. The scenarios symbolized several building envelopes with differing roof designs, external wall and floor insulation, and window schemes. Then, we compared the effect of each scenario, including yearly energy use and peak cooling demand.

4.1. Base Model Energy Validation and Functioning

Because one aim of the research was to determine how effective various building envelope strategies are for lowering energy demand in a residence in the hot, arid context of Al Ain, it was important to check the modeling outcomes to enhance the reliability of the findings. As such, official monthly electricity bills for the case study were plotted against the modeled outcomes of the case study, as presented in Figure 6. The simulated consumption almost shadowed the actual consumption, showing a significant rise in summer between May and October. This trend is expected because of the strong reliance on mechanical cooling, which comprises 60–65% of electricity consumption in buildings of this type [52].

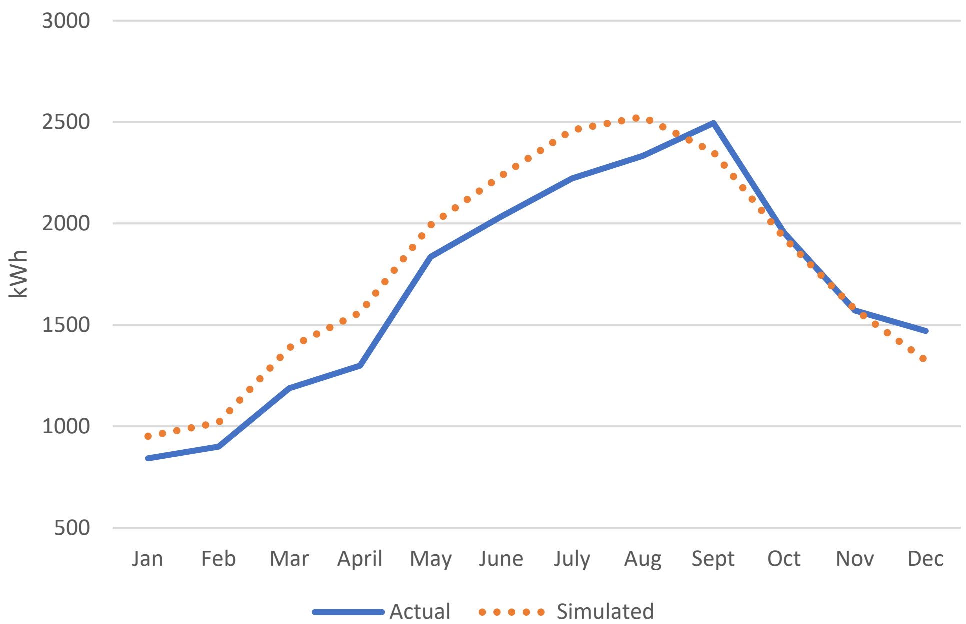


Figure 6. Actual v. modeled monthly electricity use for the base case.

Regarding root mean square error (RMSE), Equation (3) represents the magnitude of the variation between the modeled and observed responses [53]. The RMSE was 16.52%, which is still within ±20% RMSE tolerance criteria [54,55], indicating that the DesignBuilder base model captured the key features of the building's physics.

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{N} (x_i - \hat{x}_i)^{2}}{N}} \tag{3}$$

RMSE = root mean square error

i= variable i

N = number of non-missing data points

x_i = actual observations time series

$\hat{x}_i$ = estimated time series

Figure 7 presents the trend in electricity usage for the base case, showing that energy for cooling comprises 73.5% of the building's energy use. Although this is very high, it appears more typical for the GCC area, as cooling energy is responsible for 70% of yearly peak domestic electricity usage [5,56]. For these simulations, light electricity and equipment use, respectively, constitute 13.7% and 12.8% of all energy usage in the apartment, including kitchen, living room, bedroom, and household appliances (e.g., TV, washer, fridge, freezer, and water heater). In our simulations, we did not include a heating system since there is little requirement for heating in the climate under investigation.

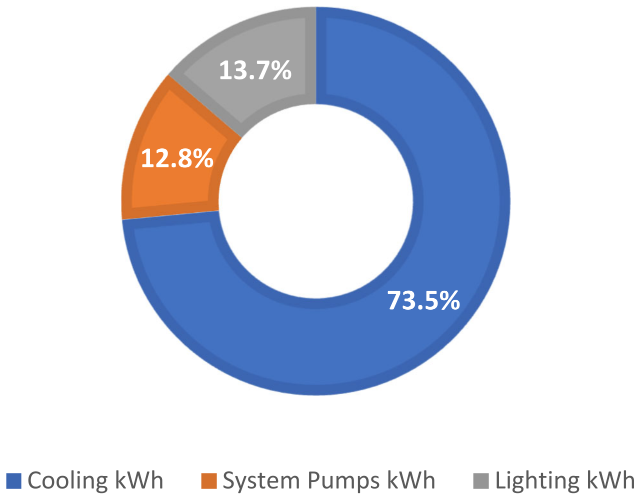


Figure 7. Electricity usage in the base case.

4.2. *A Comparative Analysis of the Influence of Various Building Envelope Approaches*

The next section covers the possible advantages of the use of various building envelope features, such as roofs, walls, floors, and windows, for the total energy performance of the base case. In turn, we present the outcomes for each scenario, followed by the respective findings of the base case. There is then a comprehensive comparison of the impact of each scenario through observation of the variations in the building energy usage to determine the maximum energy reduction via the optimum grouping of the scenarios investigated.

4.2.1. Roof Design Configurations

To explore the possible advantages of using different roofing types in a hot, arid climate, we investigated cool roofs, light-colored gravel assembly, and green roofing. The specifications for the roof types are as in Tables 3 and 4. The findings are compared with uninsulated and insulated roof configurations and the base case.

The yearly cooling system energy usage for the different roof design scenarios is presented in Figure 8. All the investigated configurations of cool, gravel assembly, and green roofs attained nearly the same decrease in yearly cooling. The three cool roof cases achieved 154.0 KWh versus 155.6 and 156.2 KWh for the green and gravel assembly roof scenarios, respectively. These are almost the same as the base case (50 mm insulation). Raising the insulation level to 150 mm lowered the yearly energy cooling to 151.2 KWh against 156.6 KWh for the 50 mm insulation of the base case. Without roofing insulation, there could be up to a 6% rise in yearly energy usage for cooling, in alignment with results for an analogous climate in Bahrain [57]. As such, we conclude that thermal insulation is paramount for the cooling load. Comparable findings were also produced by Zhao et al. [58], who investigated sensitive design features according to the climate type, insulation thickness, solar protection, and solar heat gain coefficient (SHGC) of outside windows/glass doors. They reported on the main passive energy efficiency approaches for a hot climate. The findings also revealed that other design elements, such as a green roof, sand, or light-colored gravel, had a minimal effect on the cooling load of this house. It is notable that these outcomes are based on a lighting gain of 10 W/m^2 and an equipment gain of 15 W/m^2. Moreover, heat gain, which refers to the amount of heat that enters a building from external sources, can occur through various mechanisms, including solar radiation, conduction through walls and windows, and infiltration of hot air from outside. Therefore, analyzing the heat gain breakdown for a space adjacent to the roof was crucial. Figure 9 shows that solar gain constituted 11% of total gain, and any type of improvement to the roof, although eliminating solar gain, could also prevent internal gains from being lost. However, in actuality, the amount of internal gain depends on the use of space, and thus, the energy reduction for different roof designs may change as a result.

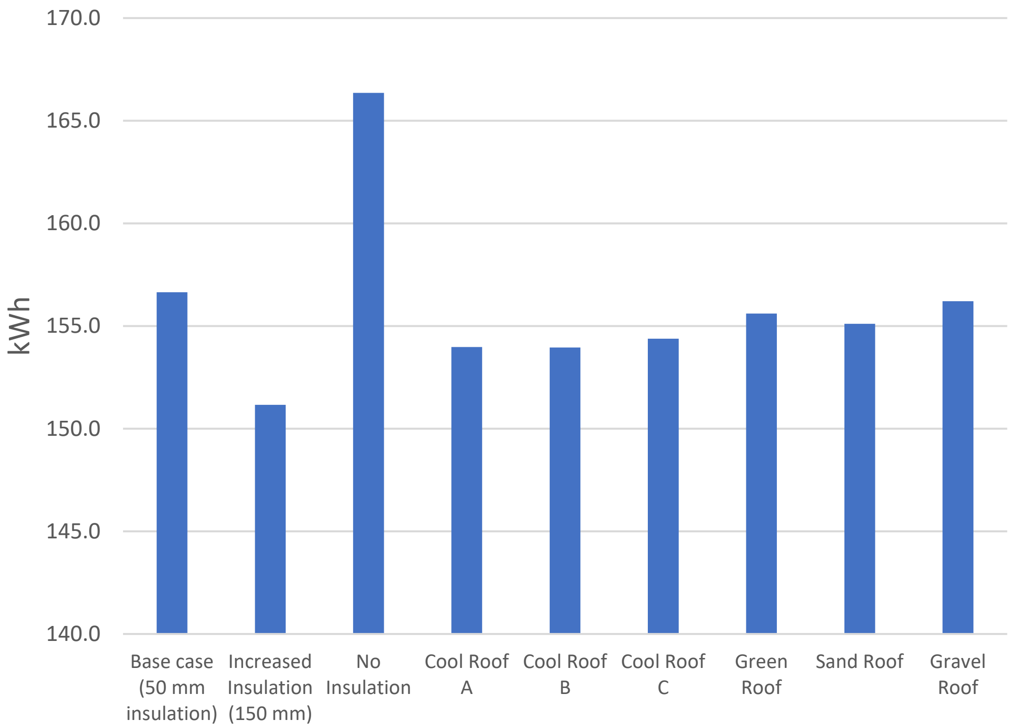


Figure 8. Yearly electricity usage for a cooling system for different roof designs.

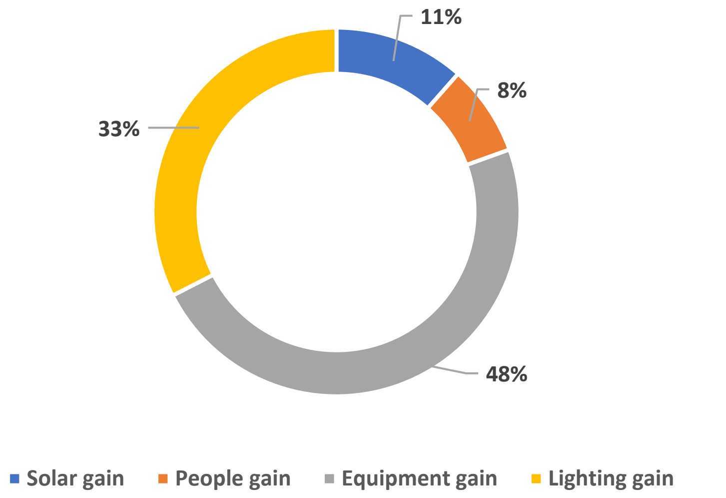


Figure 9. Heat gain breakdown analysis for one bedroom adjacent to the roof.

4.2.2. The Addition of Insulation to Outer Walls and Flooring

The modeling outcomes for the various roof design scenarios show that insulation is the key thermal aspect for reduced cooling loads in the case study. To improve our knowledge of the significance of insulation for other building features, the same strategy was used for the external walls and floor. The conduction gain breakdown was conducted for the case study in Figure 10 and compared with another room on the ground level in Figure 11 for a more detailed analysis of the conduction gain between different levels. In both cases, the gain from the external wall is the most significant, so the addition of insulation to walls will thus have a greater effect on electricity use for cooling annually. The amount of the decrease in cooling electricity use after adding insulation to the external walls is indicated in Figure 12, which shows that cooling energy could be lowered by up to 25% by adding 50 mm of insulation to the wall. If the fabric includes more than 50mm of insulation, there is a 1–2% decrease. Adopting the same strategy for insulation on the ground floor might lower cooling energy by up to 3%, as shown in Figure 13. The effect is minimal if the insulation thickness of the floor is increased beyond 50 mm.

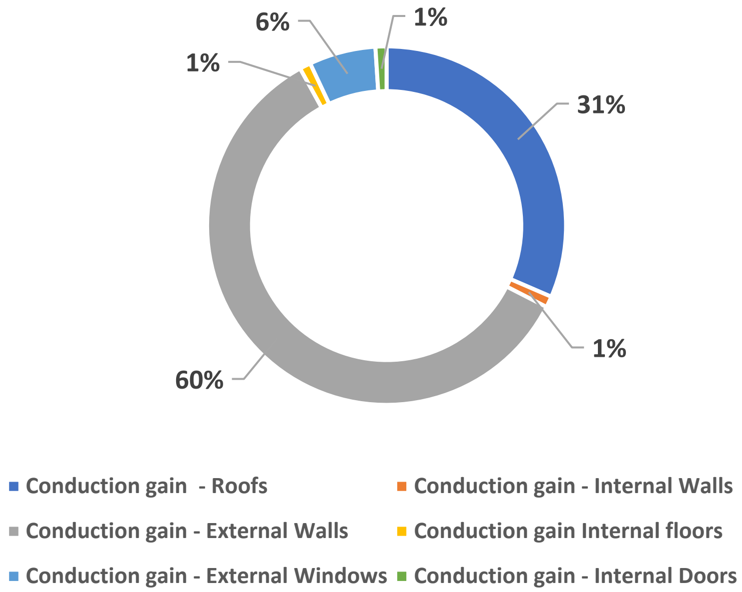


Figure 10. Conduction gains breakdown for a bedroom on the first floor.

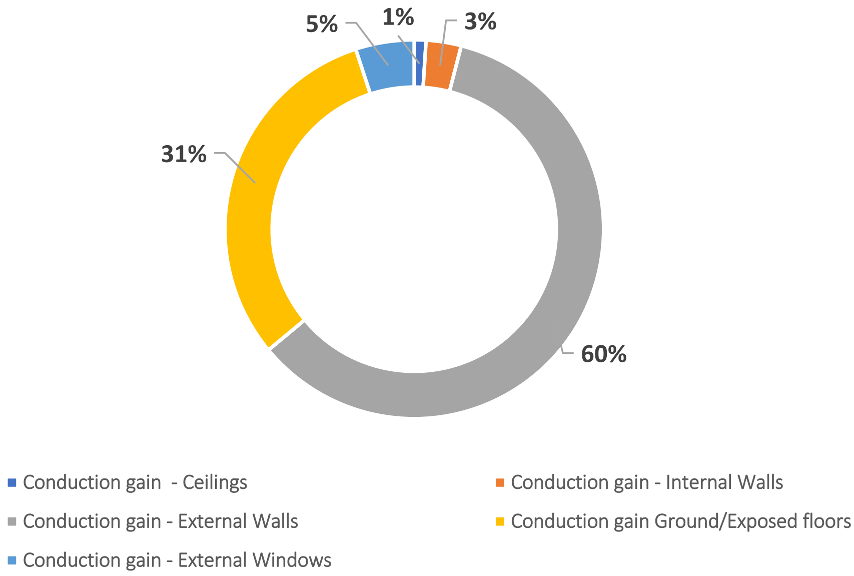


Figure 11. Conduction gains breakdown for a living room on the ground floor.

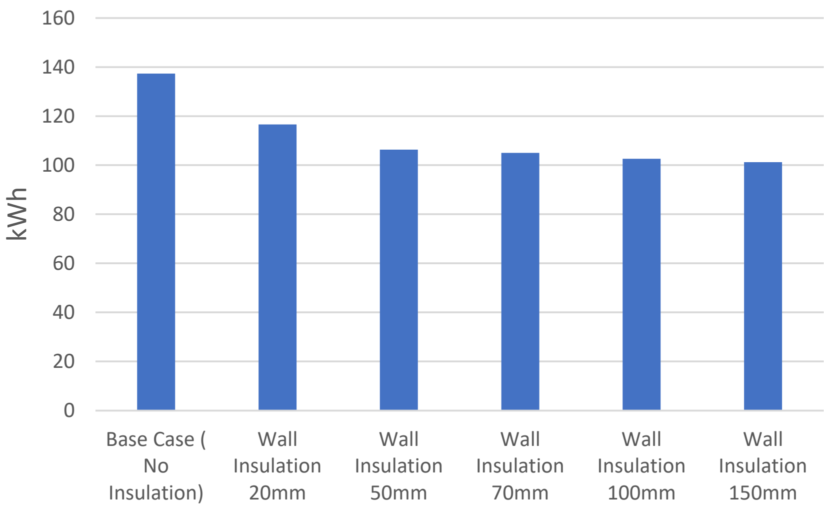


Figure 12. Cooling energy usage with insulation added to the external wall.

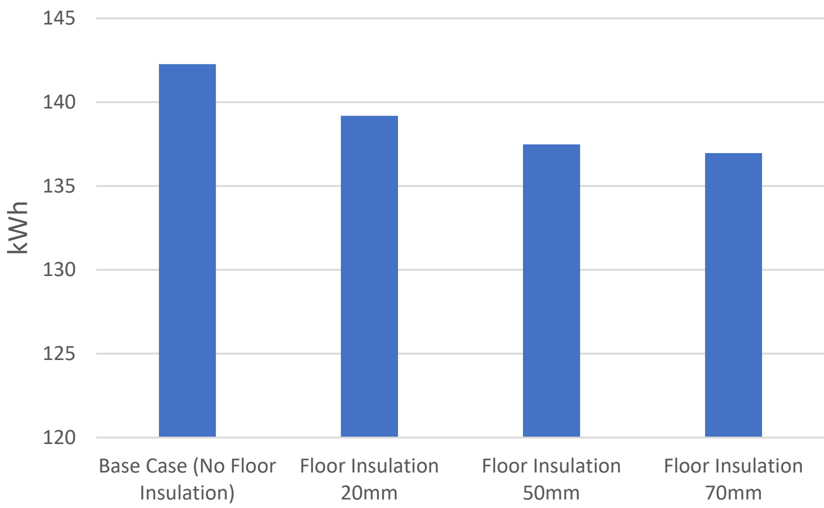


Figure 13. Cooling energy usage with insulation added to the ground floor.

4.2.3. Outer Window Designs

The conduction gain breakdown shown in Figures 10 and 11 reveals that the gain from external windows is 5–6% of the total gain. This suggests that the kind of window may have little effect on cooling energy usage in this house, possibly because of the low window-to-wall ratio of the façade in this building. Four window options were simulated in DesignBuilder to explore the effect of outer window specifications on the cooling load of the space. These window design variations and their outcomes are presented in Figure 14. These window options are all double-glazed units with various types of panes and filling gas in the cavity (e.g., air or argon). This indicates that the g-value is a more significant feature than the U-value for a hot climate, just as in the case study. In the windows A scenario, when g-value decreased from 0.4 to 0.2, yearly energy usage for cooling lowered by 1%. In the windows B scenario, despite the U-value being lowered from 3.1 to 2 W/m^2-K, cooling energy usage rose because of the higher g-value of 0.5. In the windows C and D scenarios, a greater decrease in U-value was accomplished by using low-e glazing design specifications, for example, higher inside/outside reflectivity and less emissivity for the internal surfaces. However, even with a U-value of 1 W/m^2-K, the decrease in cooling load was unable to match the windows A design option, when only the g-value was decreased.

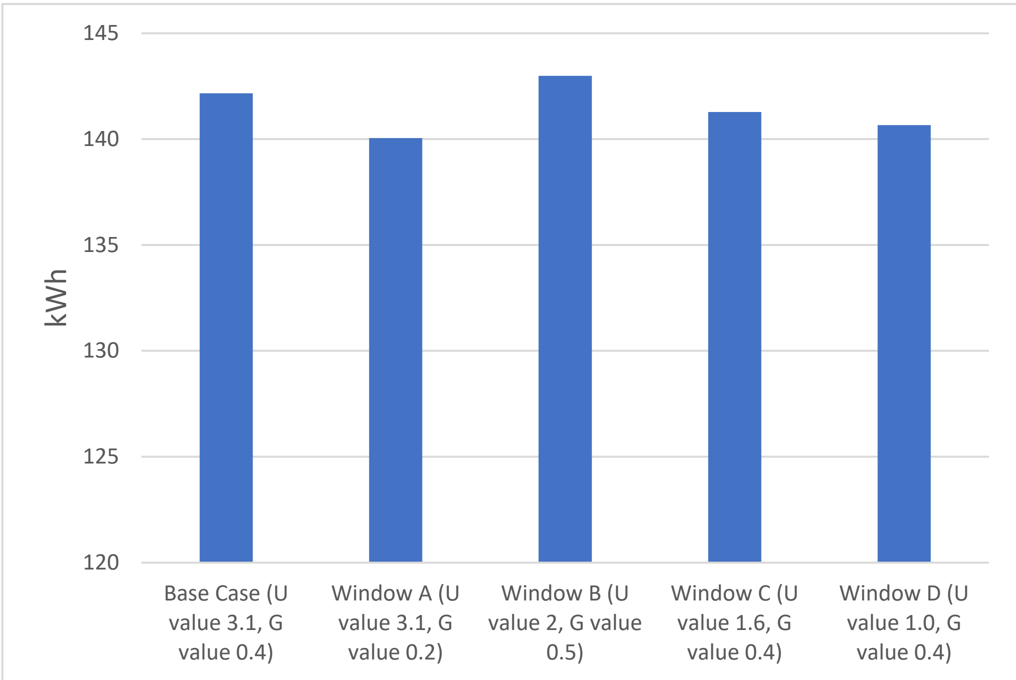


Figure 14. Cooling energy usage for various windows options.

5. Discussion

Based on simulations conducted using DesignBuilder, the results indicate that outer wall installations are the most significant fabric upgrade recommendations for residential buildings in similar arid climates, as observed in this case study. Furthermore, the addition of roof insulation can facilitate lowered cooling loads in the building. However, we conclude that the incorporation of thermal elements such as a cool roof, light-colored gravel, and a green roof seemed to have only a minimal effect on the building's cooling load when applied without thermal insulation. This finding is consistent with another study conducted in a similar climate in Dubai, where the cool roof only contributed to a 3.85% reduction in annual energy consumption [59]. Still, when applied with 50 mm thermal insulation, a 10% reduction in cooling loads can be achieved. This is despite the potential of cool and green roofs to mitigate UHI effects [49–51], which is not considered in this study.

In our case study, the window specifications did not have a significant impact due to the low window-to-wall ratio. Nevertheless, it is to be noted that window type may be a significant design factor in alternative building forms, especially those with full-glazing facades. In these cases, the g-value of windows appears to be more significant than the U-value, as the degree of solar gain incident on the windows is more important in this climate. We would also like to recognize that our outcomes are based on set levels of lighting and equipment gains in the building, which are heavily reliant on usage and operational factors.

The results of this study have stimulated other ideas and questions worth further investigation, summarized and discussed as follows:

- Type and Thickness of Insulation: Insulation was found to be an effective passive measure for reducing cooling load in arid climates. However, considering the cost of insulation, it is important to address various design considerations to ensure its effective use in buildings. Design parameters such as the type of insulation, its thickness, and the level of insulation in walls, roofs, and floors can be tailored to specific buildings. In our study, it was found that adding 50 mm of expanded polystyrene insulation to the external wall, roof, and ground floor resulted in a 25% reduction in yearly cooling energy, 6% in the roof, and 2% in the ground floor. Increasing the insulation thickness beyond 50 mm did not have a significant impact. Additionally, while adding insulation to the outer wall was the most effective construction feature, this may vary for different projects depending on the building's shape.
- Glazing Specifications: The study examined the range of U-values and g-values for glazing and found that the g-value had a greater impact. However, it is worth noting that the U-value of a window may have a larger effect on buildings with a higher window-to-wall ratio. Tinted glazing is commonly used in arid climates due to its lower g-value and cost-effectiveness. However, this choice results in reduced natural daylight and obstructed views from the outside. Alternatively, modern low-emissivity (low-e) glazing windows with clear glass can help minimize solar gain while maintaining natural daylight. However, these windows may be more expensive and unsuitable for affordable housing projects. External shading designs like Brise Soleil are another option that architects and engineers can consider for clear glazing in buildings without the additional cooling load.
- Roofing Options: Various roofing choices, such as cool and green roofs, gravel, and sand, were explored in this study. Cool roof materials with plastic or rubber blended bitumen (APP or SBB) are on the market, but there are also less expensive choices, such as gravel or sand, which can be used as roof coverings. Green roofs may cost more regarding installation, irrigation, and maintenance in this arid climate. Also, although our modeling results suggest no real improvement from any of these roofing choices, it should be observed that the roofing area is restricted in this particular house, and there is outer shading at the perimeter of the roof to minimize solar gain. The effect of roofing finishes may be more relevant for buildings with a greater roofing surface area.
- Effects of Internal Gains: In arid climates, improving the building fabric to reduce solar gain and cooling load can present challenges with heat dissipation inside the space. The effectiveness of adding insulation or upgrading surface finishes depends on the amount of internal heat gains in the space. With the increasing presence of electrical appliances in residential buildings, the cooling load may increase if heat is not externally dissipated through the building fabric or ventilation. Our study demonstrated that, for spaces adjacent to the roof, lighting accounted for 32%, and equipment gain accounted for 48% of the total heat gains. We assumed a lighting density of 10 W/m^2 and equipment density of 15 W/m^2 as typical loads in buildings. This highlights the potential effectiveness of ventilative cooling as a technique in arid climates, as it allows for the introduction of external temperatures into the internal space.

6. Conclusions

In UAE, the consumption of cooling load is more than 50% in buildings [60] and can reach 79% in residential buildings [61]. This has triggered a renewed interest in the UAE, which is facing pressure to develop its own energy-efficient building envelope regulations to meet national energy and environmental challenges. However, there are very few applications and studies on such codes in an arid climate remain very limited [20,24,25]. Hence, the aim of this research was to enhance the energy efficiency of a typical apartment situated in the hot, arid climate of Al Ain in the UAE. A building model was created to evaluate the influence of various factors, including cool and green roof features, wall and floor insulation, and the windows' g- and U-values, on the energy required to cool the building. The key results are as follows:

- Insulation: The study found that insulation effectively reduced cooling load in arid climates. Design considerations such as type, thickness, and location of insulation can be tailored to specific buildings.
- Glazing: The study examined U- and g-values for glazing and found that the g-value had a greater impact. In contrast, low-emissivity (low-e) glazing with clear glass can minimize solar gain while maintaining daylight.
- Roofing: No significant improvement was found for cooling load reduction. Roofing finishes may be more relevant for buildings with larger roof surface areas.
- Effects of Internal Gains: Managing internal heat gains is crucial in reducing the cooling load. Lighting and equipment gain accounted for a significant portion of heat gains. Ventilative cooling can be effective in dissipating heat in arid climates.

Applying passive building envelope retrofitting strategies could soon be a very promising aspect of sustainable and low-energy building design. However, it is important to note that results may vary across different climate contexts. Therefore, it is important to consider different factors such as context, climate, design requirements, and country-specific conditions when assessing building envelope retrofitting capabilities. Finally, it should be noted that the study only focused on one building type and a limited number of retrofitting strategies. Future studies could broaden the analysis to encompass other building types, including a different range of insulation types, glazing specifications, and roofing options. Furthermore, integrating additional renewable energy sources, such as solar energy, and conducting lifecycle and embodied carbon analyses will provide valuable insights into material choices for building fabrics in arid climates like Al Ain.

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