

Original Article

Evaluating Passive Envelope Strategies and Lighting Efficiency for One-Story Residential Buildings in Amman's Suburban Neighborhoods

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Abstract - Residential buildings contribute to the maximum percentage of total energy consumption in Jordan. This current study attempts to investigate the energy-saving potential associated with passive envelope design interventions along with the use of efficient lighting units. The study seeks to reduce energy consumption in a one-story residential building located in the Amman suburbs. In this regard, a model house of an area of 133 m² was constructed using DesignBuilder simulation software in order to estimate the total baseline energy consumption. This study assesses the energy-saving potentials due to the integration of various design interventions, such as the thickness of exterior wall insulation, the installation of a roof exterior coating, the addition of shading devices, the adjustment of window to wall ratio, the upgrading of glazing systems, and efficient lighting units. It has been observed that the integration of passive envelope retrofits with the insulation of LED lighting decreases the total energy consumption of the house by up to 31.8% with a significant reduction in CO₂ emissions. These findings contribute to the improvement of future frameworks for residential building retrofits in Jordan through practical methods for improving energy efficiency, outlining that climate-responsive techniques can effectively boost residential energy efficiency in Amman.

Keywords - DesignBuilder, Energy performance, Jordan, One-story housing, Passive design strategies.

1. Introduction

Buildings constitute 35% of the energy use worldwide and, remarkably, 55% of the world's electricity consumption, covering the energy consumed in the construction and operation processes as well as the direct on-site use [1]. Thus, investing in energy-efficient buildings is essential to reduce the total energy consumption on a larger scale, thereby decreasing greenhouse gas emissions. Attaining such results does not necessitate constructing new buildings; instead, it can be accomplished by retrofitting existing ones [2, 3]. From an economic perspective, improving the energy conservation of existing buildings by adopting sustainable retrofits is a more cost-effective initiative than designing new green buildings [4]. Retrofitting strategies are directly linked to the building envelope-including roofs, floors, wall systems, and openings-which significantly influence the operational energy demand for heating and cooling [5]. The building sector accounts for about 33% of worldwide energy use, and HVAC, and lighting are considered to be large sources of operational energy consumption [3]. Residential buildings make up a major share of the entire stock of buildings in many countries and cities. This calls for the significance of managing energy consumption in dwellings. Energy optimisations in residential

buildings have a direct effect on energy consumption in a global setting [6].

Jordan's housing sector comprises several building types, approximately 78% of which are located in suburban and rural areas. In suburban areas, houses, apartments, and villas made up 55%, 42%, and 2.4% of the distribution of housing, respectively, whereas in rural areas, the distributions were 88.9%, 9.9%, and 1.2% [7]. In Jordan, energy is among the growing crises due to population growth and urbanisation, especially in Amman, home to 42% of the total population. Thereby, raising the continued increase rates of the building stock by (4-5%) [8]. This situation, in turn, makes residential buildings the largest energy consumers locally [9]. Accordingly, there is an urgent need to adopt passive design methods in the Mediterranean environment of Amman to address the limited resources and unstable energy supply [10-12]. Jordan's national policy as well calls for prioritising sustainable energy solutions at both the theoretical and practical levels, though their application on the ground is still in its infancy [13]. Limited research on this topic within the Jordanian context has been conducted to date. Previous studies have focused on several active and passive design



strategies. Jaber (2002) outlined that the thermal insulation of buildings' roofs and walls contributes to decreasing the cooling and heating loads and their associated fuel energy [14]. Despite such important findings, no empirical evidence was investigated in real-world conditions through simulating the performance of various architectural interventions in residential building designs. In the Al-Ghandoor et al. (2008) study, urban households' buildings were identified to assess the quantity and quality of the operational energy, heating, lighting, and other appliances' electricity consumption, leaving multi-story and suburban buildings behind [15]. A general finding was concluded by AlZyood et al. (2010), outlining the significance of the site analysis in choosing the appropriate design response including the building's south-face orientation and well-designed heating strategies, focusing on Trombe walls and insulation). Similarly, Ali et al. (2020) studied single-family homes in Irbid, a northern city in Jordan, to optimise building envelope designs. However, conducting such a study does not allow an in-depth assessment of the effects of passive and active design elements [16]. Roofs and walls' insulation materials, solar shading, and lighting, as well as HVAC system upgrades on energy consumption was assessed for two-story residential villas across three cities (Aqaba, Irbid, and Ma'an), leaving Amman's buildings behind [17]. A more recent study by Albadaine (2022) was conducted in Amman and highlighted the importance of considering the impact of passive architectural design decisions, including building orientation, form, ratio, and zoning, on reducing total energy consumption [12]. Abu Qadourah (2022) argued that passive design interventions constitute the most effective strategies to conserve operational energy, cooling, heating, and lighting in a typical multi-family Ammani residential building. According to the study findings, energy-efficient LED lighting, solar shading, glazing, and thermal insulation materials are all significant drivers of energy optimisation [11]. Overall, existing studies underline the importance of further investigation into residential buildings in Jordan and Amman in particular in order to address current sectoral challenges and promote sustainability [18].

Although previous studies have confirmed the potential of both active and passive design interventions to reduce residential energy consumption in Jordan, several important knowledge gaps remain. Early studies primarily focused on the benefits of thermal insulation for reducing heating and cooling loads, while later investigations examined specific passive design interventions or residential energy consumption in particular building typologies and climatic regions. More recent research has evaluated individual building envelope improvements, glazing systems, shading devices, and HVAC upgrades; however, these studies either emphasised holistic architectural parameters or focused on villa-type or multi-story residential buildings. Furthermore, suburban single-story houses have received limited attention despite their substantial contribution to Jordan's residential

housing stock [19]. This gap is particularly important because suburban housing makes a large share of the residential stock in Jordan and presents substantial opportunities for increasing energy efficiency. Nevertheless, the combined effectiveness of glazing systems, solar shading, thermal insulation materials, green roof design, and energy-efficient lighting systems has not been systematically investigated for this housing typology under the climate conditions of Amman.

Therefore, the present study seeks to evaluate the energy performance of a representative one-story suburban house (Dar) in Amman by assessing the independent and combined effects of thermal insulation, solar shading devices, glazing systems, along with an efficient lighting system using DesignBuilder simulation, along with calculating their associated cost. Unlike previous studies that primarily investigated isolated passive measures or different residential building typologies, this research adopts an integrated approach to determine the optimum combination of energy conservation measures based on local climate conditions. The findings contribute new evidence for improving residential building energy performance and provide practical recommendations for architects, engineers, and policymakers seeking to promote sustainable residential development in Jordan.

2. Literature Review

Achieving improved energy efficiency of buildings calls for thorough knowledge of passive building envelope retrofits and efficient lighting strategies. The subsequent subsections provide a summary of the literature on the impact of the aforementioned strategies, which strive to optimize multi-goals, including energy consumption, CO₂ emissions, and costs.

2.1. Building Envelope Retrofits and Energy Efficiency

The inefficient envelope components in existing buildings contribute to increasing cooling and heating [2]. Therefore, building envelope retrofits are increasingly recognized as an effective initiative incorporated to enhance overall thermal performance.

The building envelope is the primary barrier controlling inward and outward heat flows, thereby impacting the energy performance of buildings [20]. However, due to improper design of the building envelope, it has become the major conduit for the passage of heat, resulting in more than 60 % loss of energy in traditional buildings [21]. The proper implementation of thermal insulation reduces unwanted heat gains and losses during summer and winter, resulting in lowering operational energy demand and improving indoor thermal comfort [22, 23]. It is necessary to consider cost, the readily available and easily accessible insulation materials in the retrofitting process of the building [6].

2.1.1. Thermal Insulation

Previous studies consistently demonstrated the efficiency of building envelope thermal insulation materials in enhancing residential buildings' energy performance. Insulated roofs and walls significantly reduced cooling and heating energy requirements [14]. In the Jordanian context, owners and related authorities tend to overlook and ignore implementing proper thermal insulation in residential buildings [2].

Walls and roofs retrofit involves adding different types of insulation, including external and internal insulations or internal and external cladding [21]. The insulation material could be added to either the internal or external face walls and roofs [2]. Roofs are considered the main solar heat acquisition points in buildings since they permit a significant amount of heat transfer [17]. In their multi-criteria retrofitting study, Ruá et al. (2024) determined that 20% of energy saving was gained from the roofs, thus making the roof the highest heat-transferring component of the building envelope [24].

Likewise, other studies found that improving insulation decreases peak cooling loads and contributes to better thermal comfort, specifically in Mediterranean and hot arid climates [17, 23]. However, insulation performance is determined not only by material characteristics but also by the thickness of the insulation and climate conditions. Increasing insulation thickness beyond an optimum level may produce diminishing energy savings while reducing the effectiveness of passive cooling during warmer periods [17]. For one-story buildings, the roof is considered the primary source of solar heat gain due to its direct, continuous exposure to the sun, thereby allowing significant heat transfer [17].

Buildings' exterior walls further impact the interior space's temperature and heat transmission. Accordingly, choosing high thermal resistance insulation material with appropriate thickness is essential to minimize the heat transfer portion [23]. While adding insulating layers to the walls helps reduce heat flow, the addition of excess thickness to the walls might decrease the efficiency of the passive cooling system [17].

Green roofs also effectively reduce building demand, while they have a significant impact on one-story buildings, as their roofs contribute the most to heat gain and loss. A green roof consists of vegetation installed above a waterproof insulation system, reducing the roof surface temperature by shading the roof and increasing evapotranspiration [25]. Previous research has shown that green roofs improve roof thermal resistance and contribute to urban heat island mitigation [26]. Their effectiveness depends on vegetation type, soil depth, irrigation, climate conditions and maintenance requirements. While green roofs have demonstrated positive environmental performance, relatively few studies have evaluated their combined influence with other passive design interventions in residential buildings

located in Mediterranean climates. The incorporation of multiple envelope retrofits provided greater energy savings than individual measures alone [27, 28].

2.1.2. Windows and Glazing Types

The windows in buildings are among the most important parts of the building envelope due to their simultaneous ability to control heat flow, sunlight, ventilation, and daylight availability. Approximately 20-40% of total building energy losses may occur through poorly designed and installed windows [29, 30]. Several studies have demonstrated that window performance depends on orientation, glazing type, and window-to-wall ratio, characteristics that control light, thermal and solar transmittance [22, 23]. This indicates that windows directly contribute to the thermal comfort of the interior architectural space, ventilation, and natural lighting. Such performance measures also impact the total energy consumption [31]. For instance, upgrading single glazing to double and triple glazing types positively impacts the energy consumption rates [32] due to reduced heat transfer and improved energy efficiency because of lower solar and thermal transmittance. Additionally, using an insulated frame reduces heat transfer through the windows. Furthermore, the opening mechanism of the windows and their construction highly affect the envelope air leakage [23]. Accordingly, window design in terms of orientation and size, type and material selection should be carefully considered to balance thermal performance with daylight availability and winter solar heat gains [22]. Of all the three mentioned glazing types, double-glazed windows are the most practical and cost-effective for use in Jordan [2].

2.1.3. External Shading Devices

External shading systems present an effective strategy, if designed well, to control the entry of solar radiation by preventing unwanted solar radiation during summer and allowing its entry in winter [27]. Previous studies indicate that appropriately designed shading systems reduce cooling loads in hot months and allow solar entry and reduce heating load in cold months, increasing occupant comfort while maintaining acceptable daylight, leading to higher amounts of energy savings [17, 33]. Different forms of shading systems, including the use of vegetation, fixed overhangs, vertical fins, movable ones, and smart kinetic shading technologies, are implemented to minimize the building energy consumption. Nonetheless, adding shading devices near windows can also affect the amount of incoming daylight [35]. The efficiency of the shading systems depends on several factors, including orientation, dimension, geometry, material, and climate conditions [22]. In Jordan, external shading systems are generally constructed using Aluminum or reinforced concrete [2].

2.2. Energy-Efficient Lighting as a Building System

Lighting contributes directly to electricity consumption while also influencing internal heat gains. Consequently,

lighting selection affects both electrical demand and cooling energy requirements [35]. Daylighting reduces the need for artificial lighting but may introduce additional solar heat gains. Therefore, lighting design requires balancing visual comfort, daylighting utilization, and energy efficiency [7]. Thus, selecting the proper lighting units is not a simple task. It is built on a trade-off between luminous flux, temperature, and electricity consumption. Among available lighting technologies, LED systems consume considerably less electricity while generating lower internal heat gains than conventional lighting systems [36].

2.3. Integrated Retrofitting Strategies and Building Simulation

Recent studies demonstrated that combining multiple retrofitting strategies produces greater energy savings than implementing individual measures independently [27, 28]. Consequently, integrated design approaches have become an important focus of residential energy-performance research.

Several simulation-based studies have reported substantial improvement from integrated design strategies. Mousavi et al. (2022) found that combining thermal insulation, reflective coating, low-emissivity glazing, and external shading reduced annual energy consumption by more than 50% while increasing thermal comfort hours by approximately 45% in Mexico's climate [37]. Similarly, Mushtaha et al. (2021) reported that incorporating thermal insulation, solar shading, as well as natural ventilation reduced building energy consumption by 59% in Gaza multi-story residential buildings [27].

Similar results were reported under different Cyprus climatic conditions, Bekele and Atakara (2023) reported that combining window improvement, building orientation, external shading, and infiltration achieved around 34.7% energy saving [28]. Ping Liu et al. (2025) found that a combination of several envelope retrofit methods, including window-to-wall ratio, roof and exterior wall insulation, greatly enhance the energy saving amounts, reaching 46.8-70.5% in a rural residential building in China [38]. Al-Tamimi (2022) found that thermal insulation, varied types of glass, shading methods, and green roof decrease annual energy consumption by 35.4% in multi-story buildings in Sharurah city, KSA [39]. In the Jordanian context, Abu Qadourah et al (2022), found that wall insulation, shading, natural ventilation, and lighting of multi-residential buildings are important factors in energy saving, resulting in energy savings of 78%, 71%, and 53% in lighting, heating, and cooling, respectively [11].

Although previous studies highlighted the benefits of integrated retrofit design, the reported energy saving vary considerably because of differences in climate, building typology, occupant pattern, baseline construction, and simulation assumptions. These variations demonstrate that

retrofitting strategies depend on contextual conditions and must be evaluated under local climatic conditions rather than transferred between regions. Building performance simulation provides a reliable framework for evaluating the interactions between retrofitting strategies under changing weather conditions while maintaining a consistent baseline for comparison. DesignBuilder with EnergyPlus simulation is among the most popular tools used to assess residential building energy performance before implementation.

2.4. Research Gap

The reviewed literature confirmed that retrofit strategies can substantially improve residential building energy consumption. However, relatively few studies have comprehensively evaluated the combined impact of external solar shading devices, glazing systems upgrades, thermal insulation alterations, and LED lighting for suburban single-story houses within Amman's climate. Moreover, while previous studies investigated the impact of glazing systems and WWR modification on energy consumption, limited attention has been given to their simultaneous impact on indoor daylight availability and visual performance. Consequently, evidence-based guidance on optimizing both energy efficiency and daylighting through integrated retrofitting strategies for this important residential typology remains limited. Retrofitting strategies associated cost analyses were also overlooked in the previous studies.

To address these gaps, the present study employs dynamic DesignBuilder simulation to evaluate the independent and collective impact of multiple active and passive design interventions on annual cooling, heating, lighting, as well as total energy consumption. Furthermore, the present study investigates how different window configurations and glazing systems influence indoor daylight performance, enabling a more comprehensive assessment of design alternatives. This study further guides wise design of shading devices to maximize its positive impact on energy consumption. By integrating energy and daylight analyses within the same simulation framework, along with cost analysis, the study provides practical recommendations for optimizing retrofit design strategies in suburban residential buildings under the climatic conditions of Amman.

3. Materials and Methods

A case study of one-story houses in Amman was selected within the architectural context of Jordan's urban housing stock to assess their energy performance. The study underlines how architectural design decisions can be responsive to user needs and energy demands, as well as the climatic conditions and site forces. The present study applied a simulation-based approach using DesignBuilder to assess energy consumption in one-story houses in a suburban neighbourhood in Amman. The retrofit process generally involves four main phases: building assessment, retrofit design, implementation, and post-retrofit evaluation [3]. This research concentrates on

these stages by examining the current performance of the existing residential building and determining the effectiveness of the suggested passive envelope measures and lighting through building energy simulation. Figure 1 shows the adopted workflow for energy process analysis.

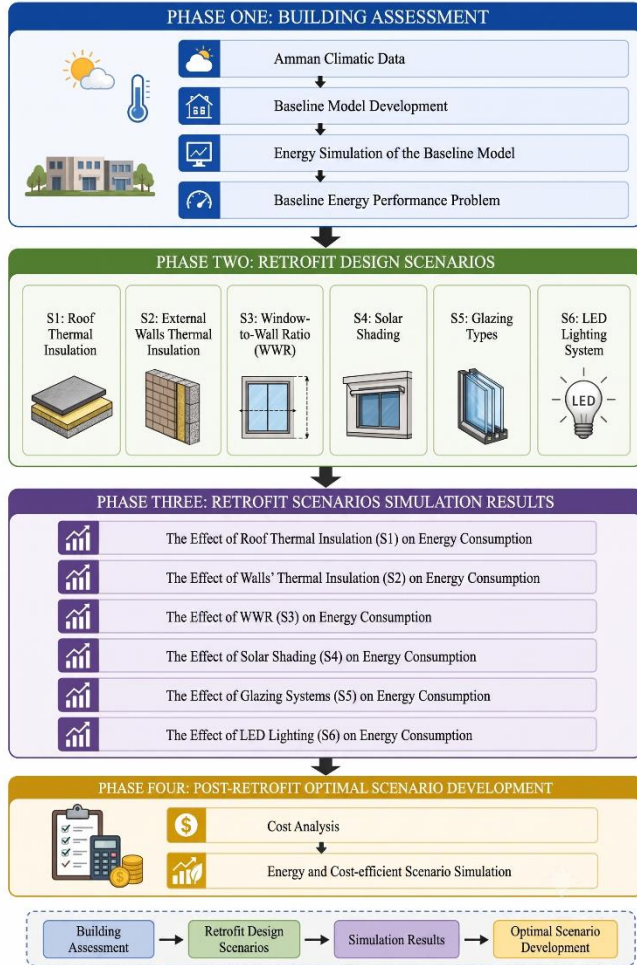


Fig. 1 Research methodology adopted for the energy performance assessment of the baseline model and design scenarios Source: Authors

3.1. Building Assessment

3.1.1. Amman Climatic Data

Jordanian climate is mainly characterised by its Mediterranean nature, with high temperatures leading to hot and dry summers and low temperatures resulting in wet and cool winters [40]. Jordan is divided geographically and topographically into: The Jordan Valley; the Desert; and the Highlands Region (Mediterranean climate) [41]. The case was modelled and simulated under Amman's suburban neighbourhood climatic conditions, which refers to the Highlands Region (Mediterranean climate). The elevation of the area is 788 meters above sea level. The longitude is 35°93'E and the latitude is 31°95'N. July is the hottest month with a 26°C temperature average; January is the coldest month with a 9°C temperature average, while January is the wettest

month with 16.8 mm on average, and July is the windiest month with approximately 13 km/h on average [42]. Though this study was conducted in the geographic particularity of Amman, the used workflow for energy process analysis can be implemented in similar climatic conditions, allowing for a broadened applicability. Weather data for Amman was obtained from the EnergyPlus weather database integrated within DesignBuilder. A dynamic annual weather file was used to capture seasonal variations in outdoor temperature and solar radiation throughout the simulated period.

3.1.2. Baseline Model Development

One of the critical considerations that played an essential role in choosing the one-story house (Dar) for this study is the relatively high proportion of such type in Jordan's building stock [7]. The selected house was designed to accommodate the occupancy of a family of eight. It is a detached unit with a rectangular-shaped layout. The total area of the building is 133.17 m². Its interior zoning was designed with a guest room, a living room, a dining room, 3 bathrooms, 3 bedrooms, and a kitchen, as shown in Figure 2. The building's main elevation is oriented towards the north. Drawings and other contextual data have been gathered to create a digital model of the selected building in the DesignBuilder workspace Figure 3. Then, the thermal zones and their distinct load conditions were identified.



Fig. 2 Architectural layout of the baseline one-story residential building used in the simulation

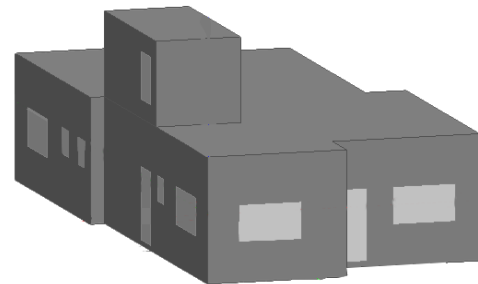


Fig. 3 The 3D model for the baseline case

The DesignBuilder model was validated according to the real characteristics of the case study building. Table 1 illustrates the key characteristics of the baseline model. The baseline building represents conventional residential construction practices, occupancy schedules, HVAC and

lighting systems in Amman and serves as the reference case against which all passive and active design interventions were evaluated.

Table 1. Baseline model characteristics

Characteristics	Description
Building model	One-story house
Orientation	North
Total floor area	133 m ²
Number of floors	1
Number of occupants	8
Window size	(2 m) width, (1.2 m) length
Outer wall	50 mm for limestone 100 mm for concrete 50 mm for EPS 100 mm for hollow concrete 25 mm for plaster
Inner wall	25 mm for plaster 100 mm for hollow concrete block 25 mm for plaster
Window-to-Wall Ratio (WWR)	20%
Roof construction	30 mm for tiles 20 mm for mortar 100 mm for reinforced concrete 140 mm for hollow concrete block 25 mm for plaster
Floor	30 mm for ceramic floor tiles 60 mm for floor screed 50 mm for sand and gravel EPS 50 mm 70 mm for concrete 150 mm for sandstone
Glazing	6mm for single clear
Glazing specifications	Direct solar transmission 0.775 Total solar transmission 0.81 Light transmission 0.881
Shading	No shading devices
Infiltration	0.5 ACH
Cooling set-point	26 C
Heating set-point	22 C
COP for heating	0.8
COP for cooling	2.0
Lighting power density	28 W/m ²
HVAC system	Split + separate mechanical ventilation

3.1.3. Energy Simulation of the Baseline Model

The energy consumption of each intervention was analysed using DesignBuilder, a dynamic building performance simulation platform that calculate building energy use, thermal comfort, daylighting, and carbon

emissions. DesignBuilder performs these calculations using the EnergyPlus simulation engine. Both tools are widely used, as they have been extensively tested and validated, demonstrating their reliability as dependable simulation tools for building energy analysis [43]. A climate data was obtained through EnergyPlus according to the location specified. In this study DesignBuilder was used to compare the performance of different interventions rather than to predict the exact energy consumption of a specific dwelling. Consequently, all design scenarios were assessed under identical modelling assumptions to ensure consistent comparison. This, in turn, facilitates an accurate representation of temperature fluctuations and their impact on cooling/heating demands [44].

Before conducting the simulations, a daily occupancy schedule representing a family of eight was established, and HVAC settings were defined to maintain thermal comfort when occupants were present. dynamic hourly simulations were then conducted in DesignBuilder over an entire year, accounting for continuously variations in climatic conditions, including outdoor temperature and solar radiation. Only the design interventions were changed between simulation scenarios, allowing their effect on the annual energy consumption of the one-story house (Dar) to be evaluated against the baseline.

3.1.4. Baseline Energy Performance

The baseline case consumes 11.44 kWh for cooling, 9.75 kWh for heating, and 7.04 kWh for lighting. Heat gains and losses were also evaluated. Figures 4 and 5 present the transmission gains and losses during both cooling and heating periods. Roofs are responsible for 35% of the total transmission losses, while the walls account for 34% and windows 31%. Similarly, 45% of heat gain is transmitted through the roof, 35% from walls, and 20% from windows.

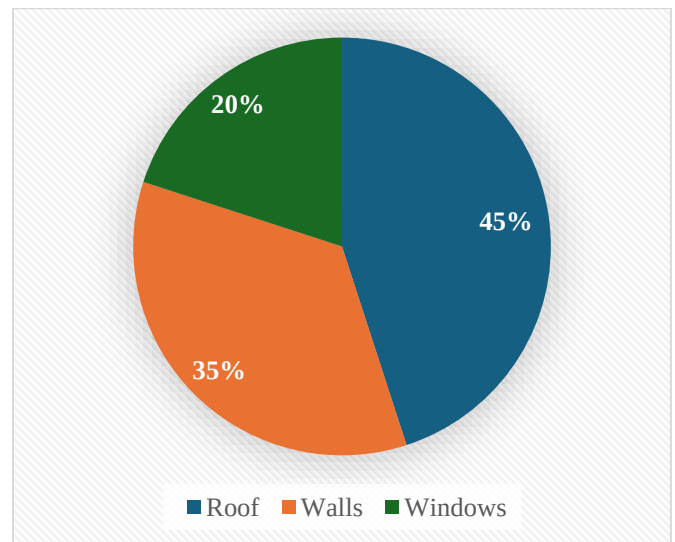


Fig. 4 The baseline envelope elements' transmission losses in the heating period

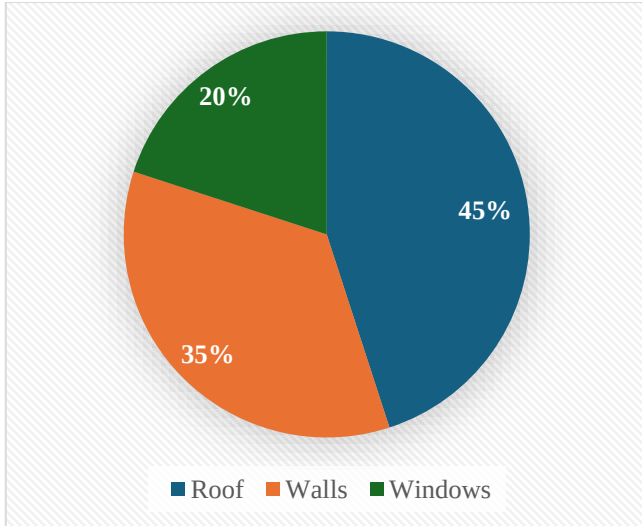


Fig. 5 The baseline envelope elements' cooling transmission gains

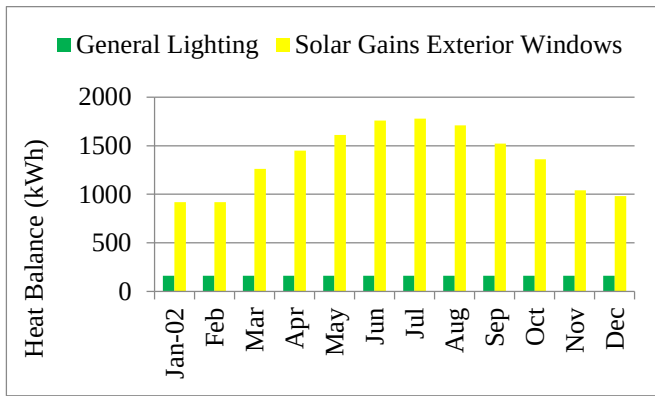


Fig. 6 Monthly distribution of heat gains from lighting and solar radiation

At the other end of the spectrum, the yearly simulation results indicate that the exterior windows are responsible for entering solar gains, contributing to increasing the total internal gains, as shown in Figure 6. On hot summer days, the cooling design is particularly active, especially during sub-hourly calculations. Consequently, the rate of carbon dioxide emissions increases during the summer when the cooling systems are operating, reaching 515 kg. The baseline model simulation indicated that the building's roof, walls, and windows contribute the most to the total heat losses and gains. This information, in turn, contributes to the heating and cooling design capacities. According to the data derived from the simulation, the base-line model annually consumes 6310.20 kWh/year of energy.

3.2. Retrofit Design Scenarios

Retrofitting scenarios during this phase have been identified based on the energy performance of the baseline case. Roof and wall thermal insulation, window size and glazing type, and shading system were all determined as building envelope retrofitting strategies. While lighting was also investigated as a building system due to its influential effect on the operational energy. Accordingly, a series of simulation scenarios, shown in Table 2, was developed using the same baseline model. S0 is the conventional/existing building, while S1–S6 are the individual retrofit scenarios, followed by the combined optimum scenario. Each one of the design interventions was evaluated separately, and then various alternatives were combined to deliver an optimum design for the building envelope parameters. The goal is to minimize the total energy consumption in accordance with local climatic conditions.

Table 2. Retrofit design scenarios

Scenario	Retrofit Measure	Baseline Specifications	Proposed Specification (s)
S0	Reference Building	Existing configuration	Baseline model
S1a	Roof Insulation	Conventional roof (U-value = 0.938 W/m ² K)	Green roof (U-value = 0.525 W/m ² K)
S1b			Roof insulation exterior coating (U-value = 0.397 W/m ² K)
S2a	External Walls Insulation	Expanded Polystyrene (EPS) = 50 mm	EPS = 60 mm
S2b			EPS = 80 mm
S3	WWR	20%	12%
S4	Solar Shading	No shading device	Fixed horizontal overhang
S5a	Glazing Type	Single clear glazing (6 mm, U = 6.121 W/m ² K)	Double glazing (U = 2.761 W/m ² K)
S5b			Triple clear glazing (U = 0.993 W/m ² K)
S6	Lighting System	Fluorescent lamps	LED lighting

3.2.1. S1: Roof Thermal Insulation

The roof in the baseline model is constructed from tiles, mortar, reinforced concrete, hollow concrete block, and plaster. It has a U-value of 0.938 W/m²-k, representing a high thermal transmittance and low thermal resistance. The U-value is relatively high compared to the U-value of roofs in the green buildings in Jordan [2]. When considering a one-story housing type (Dar), it is assumed that the roof contributes significantly to the cooling load during the summer months. To enhance the thermal performance of the baseline roof, two retrofit measures are considered (Table 3). The first measure includes installing the green roof, which enhances the thermal mass and lowers surface temperatures. A green roof was proposed as an energy-efficient alternative to reduce air temperatures and decrease the cooling load [25]. The second retrofit measure includes applying a reflective white roof coating. Reflective coating enhances the solar reflection of the roof and reduces solar heat absorption [45].

Table 3. The layer description of the original and green roofs

Scenario	Layer description	Thickness	U-value (W/m ² -k)
S0: Baseline	Tiles		0.938
	Mortar	30 mm	
	Reinforced concrete	20 mm	
	Hollow concrete block	100 mm	
	Plaster	140 mm	
S1a: Green roof	Vegetation	25 mm	0.525
	Mud	100 mm	
	Natural rubber	100 mm	
	Bitumen	40 mm	
	Mortar	100 mm	
	Reinforced concrete	20 mm	
	Hollow concrete block	100 mm	
S1b: Roof insulation exterior coating	Plaster	140 mm	0.397
	Coating	25 mm	
	Tiles	2 mm	
	Mortar	30 mm	
	Reinforced concrete	20 mm	
	Hollow concrete block	100 mm	

3.2.2. S2: External Walls Thermal Insulation

Thermal insulation has a direct impact on the total heat gains and losses in buildings [46]. In this study, the impact of increasing the thickness of the insulation material on energy consumption was examined. EPS was added as insulation to the external walls. In the baseline case, EPS thickness was 50 mm; then it increased up to 60 mm and 80 mm, respectively

(Table 4). The two altered EPS thicknesses were evaluated to assess their prospective impact on energy reduction. Insulation can be added to the walls, either internally or externally depending on the construction method, the desired results, building statue whether it is new or existing one [2]. The U-value as per building codes in Jordan for external walls is 0.57 W/m²K. Considering this value, the external wall in the baseline is not designed to minimize heat transfer as well as conserve energy [8].

Table 4. The layer description of the wall's insulation

Scenario	Layer description	Thickness	U-value (W/m ² -k)
S0: Baseline	Limestone Concrete EPS Hollow concrete Plaster	50 mm 100 mm 50 mm 100 mm 25 mm	0.72
S2a: Walls Insulation/ EPS 60mm	Limestone Concrete EPS Hollow concrete Plaster	50 mm 100 mm 60 mm 100 mm 25 mm	0.64
S2b: Walls Insulation/ EPS 80mm	Limestone Concrete EPS Hollow concrete Plaster	50 mm 100 mm 80 mm 100 mm 25 mm	0.53

3.2.3. S3: Window-to-Wall Ratio

In the baseline model sun-exposed facades, windows were designed with a 6 mm single clear glass, surrounded by an aluminum frame. The baseline model window dimensions were as follows: (2 m) width and (1.2 m) length, WWR= 20%. Then simple modifications were made to these dimensions to examine their role in reducing energy demands, as demonstrated in Figure 7. WWR should be optimized as an integral element of envelop design. An increased WWR value will result in an increase in the amount of solar radiation in the building, which may lead to cooling loads. A reduction in WWR will minimize any heat gains that are not desirable [47].

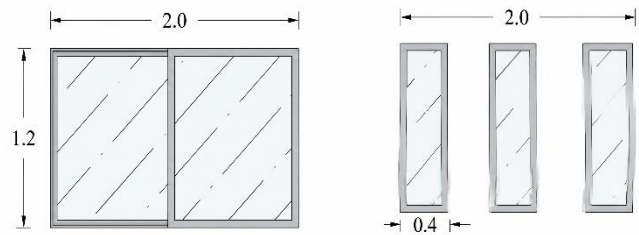


Fig. 7 Window dimension variations

3.2.4. S4: Solar Shading

Shading efficiency is determined by the building orientation, climate, type of shading and whether it can adjust for the changing angles of the sun rays throughout the year [47]. The wise selection of the appropriate type of shading devices affects the cooling energy demands for interior spaces. Installing shading devices on the southern facade controls the entry of sunlight. In the context of this study, overhang shading devices were used to passively reduce energy consumption, as illustrated in Figure 8.

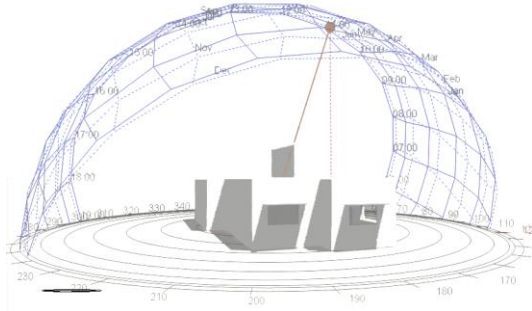


Fig. 8 Sun path diagram on 15 July at 11 am for the proposed design of the overhang shading device

The fixed canopy design was integrated into the baseline model due to its economic viability as well as design simplicity [33]. Its size was designed in accordance with predefined formulas. For instance, the horizontal overhang's length depends on the sun's specific altitude angle. Thus, the design specifications for the chosen shading device were calculated using Saifelnasra's shading device design chart [48], as follows:

The depth of the overhang is determined by Equation 1.

$$d = \frac{d}{h(h)} \quad (1)$$

$$d = 0.70m$$

The protrusion of the overhang is determined by Equation

2.

$$\rho = \frac{p}{h(h)} \quad (2)$$

In the 11-13 cut-off hours: $p = 0.35m$

In the 1-14 cut-off hours: $p = 0.85m$

In the 9-15 cut-off hours: $p = 1.42m$

The length of the overhang is determined by Equation 3:

$$l = \frac{w + 2(p)}{1} \quad (3)$$

in the 11-13 cut off hours

$$l = 2.7m$$

(l) refers to the length of the overhang.

(w) refers to the width of the window.

(p) refers to the horizontal projection (protrusion) of the overhang.

(h) refers to the height of the window.

(p/h) refers to the ratio between the projection of the overhang and the window height.

3.2.5. S5: Glazing Types

Energy-efficient glazing systems act as moderators to reduce electricity use due to their role in controlling solar heat gains. An appropriate glazing system option is crucial to prevent solar heat gain inside the building. To assess their impact, a single 6 mm clear pane of glass was used in the baseline model. Then, it was replaced by double and triple clear glazing systems, respectively. Table 5 outlines the thermal properties of the three glazing systems. Glazing performance depends on lowering the transmission of solar heat gains through windows, thereby decreasing cooling demands and improving the total energy efficiency. Referring to the Jordanian local codes, the U-value for glazing should not exceed 3.00 W/m².K, when the WWR is (10-40%) [8].

Table 5. Types of glazing

	Glazing System	Layer Description	U-value (W/m ² -k)
S0	Single	6mm Glaze	6.121
S5a	Double	3mm Glaze, 13mm Air, 3mm Glaze	2.761
S5b	Triple	3mm Glaze, 6mm Air, 3mm Glaze, 6mm Air, 3mm Glaze	0.993

3.2.6. S6: LED Lighting System

Fluorescent lighting units were selected to illuminate the building's interior zones in the baseline model. Upgrading to LED lighting is expected to directly reduce energy consumption and indirectly lower heat gains and cooling load [8].

The present study focuses on comparing alternative design scenarios using a validated simulation platform. Although the model was not calibrated against measure energy consumption data, all scenarios were evaluated under identical modelling assumptions, allowing reliable comparative assessment of the proposed retrofit strategies.

4. Retrofit Scenarios Simulation Results

The impact of each selected design intervention on energy reduction was evaluated and compared with the results obtained before and after its application. The results of previous studies are largely consistent with the present findings associated with the residential buildings' energy performance within a Mediterranean context. However, the

present findings considered a higher number of passive design retrofits to a single-story house situated in a suburban neighborhood in Amman.

4.1. Energy Performance of Individual Retrofit Scenarios

This section presents the energy performance of the individual retrofit scenarios. Each intervention was simulated separately and compared with the baseline case under identical occupancy, HVAC, and climatic conditions. This comparison demonstrates the influence of each retrofit measure on the building's annual energy consumption and identifies the most effective interventions.

4.1.1. Impact of Roof Retrofit Scenarios on Energy Consumption (S1)

The results from the simulations show that the application of roof thermal insulation considerably improved the thermal performance of the building as compared to the baseline case. The findings indicate that a green roof can decrease 11.3% of the cooling design capacity and 17.1% of the heating design capacity. Such ratios were justified by the role of the vegetated roof layer in limiting solar heat gain.

Likewise, heating performance was enhanced by reducing heat loss, allowing for a 17% decrease in the heating design capacity. Hence, the total energy consumption decreased from 6310.20 kWh/year to 6125.65 kWh/year, accounting for a reduction of 2.93% annually, as shown in Table 6. It is found that the green roof helps to improve the energy efficiency of the building and minimizes its negative effect on the environment.

Table 6. Impact of green roofs on energy consumption

Scenario	Heating capacity (kW)	Cooling capacity (kW)	Energy consumption (kWh/year)
S0	9.75	11.44	6310.20
S1a	8.08	10.15	6125.65

Installing green roofs on one-story houses in Amman directly conserves energy. The significance of the present findings lies in their focus on residential buildings, particularly one-story houses in a suburban neighborhood in Amman. Albadineh (2022) [12] investigated the energy conservation of the same residential building type, leaving green roofs' energy performance behind. Similarly, Abu Qadourah (2022) studied typical multifamily houses' energy

consumption patterns, considering a wide range of passive design interventions [11] except green roof systems. Although a green roof can considerably reduce heat transmission to indoor spaces, it places additional structural loads on the building.

To address this challenge, roof insulation exterior coating was installed as a reflective material, decreasing the capacity for cooling from 11.44 kW to 9.31 kW, indicating an 18.6% reduction. Annual energy usage also decreased from 6310.20 kWh/year to 5910.37 kWh/year, saving 399.83 kWh/year or 6.34% energy per year. Comparing the influence of both strategies, the roof coating represents a better retrofitting strategy to implement in one-story existing housing (Dar).

Table 7. Impact of roof insulation exterior coating on energy consumption

Scenario	Heating capacity (kW)	Cooling capacity (kW)	Energy consumption (kWh/year)
S0	9.75	11.44	6310.20
S1b	9.04	9.31	5910.37

4.1.2. Impact of Walls' Thermal Insulation on Energy Consumption (S2)

Table 8 shows the influence of altering the thickness of EPS material on energy consumption. A 34% reduction in the overall heat loss is attained by replacing a 50 mm EPS layer with an 80 mm EPS layer, resulting in a reduction of 8% in heating design capacity and a 5% reduction in the cooling design capacity. Thus, it can be concluded that enhancing walls' thermal insulation materials lessens external heat gains ratios and lowers the buildings' cooling requirements.

Higher insulation thicknesses work efficiently when it comes to decreasing the thermal conductance across the building envelope. As derived from the simulation results, a change in the thickness layer from 50 mm to 60 mm and 80 mm can lead to energy savings of 0.69% and 2.6%, respectively. This in turn leads to a 2.4% reduction in CO₂ emissions. This shows that a thicker layer of insulation materials improves energy efficiency and reduces the carbon footprint due to reduced heating and cooling requirements. This conclusion corresponds to the results obtained previously [10-12] but focuses on the case of a one-story building typology in Amman.

Table 8. Impact of thermal insulation thickness on energy consumption

Scenario	Thickness (mm)	Heating Capacity (kW)	Cooling capacity (kW)	Energy consumption (kWh/year)
S0	50	9.75	11.44	6310.20
S2a	60	9.51	11.29	6266.55
S2b	80	8.95	10.89	6145.98

4.1.3. Impact of WWR on Energy Consumption and Daylighting (S3)

The effect of WWR alteration on energy performance for one-story or multifamily residential buildings in Amman was out of the scope of the previously mentioned studies. On the other hand, the present study findings underline how important it is to make design-responsive decisions; the building's facade windows should be opened in accordance with the local climatic conditions.

Table 9 clearly demonstrates that modifying WWR on the four elevations decrease the building's energy demand by 9.67%.

Table 9. Impact of WWR on energy consumption

Scenario	Heating Capacity (kW)	Cooling Capacity (kW)	Energy Consumption (kWh/year)
S0	9.75	11.44	6310.20
S3/all facades	9.19	9.21	5700.11
S3/southern facade	9.55	11.05	6202.93

Such alterations in the building energy consumption also decrease the CO₂ emissions amount from 3813.12 kg to 3459.22 kg. Minimal adjustments to the facade's opening considerably conserve energy.

On the contrary, the simulation results indicate that modifying the size of all facades' openings significantly impacts the daylight distribution, as shown in Figure 9 and Figure 10.

In the optimized building design, window sizes were modified only on the southern facades to maintain a proper daylight distribution in the interior spaces, contributing to 1.7% reduction in the energy demand.

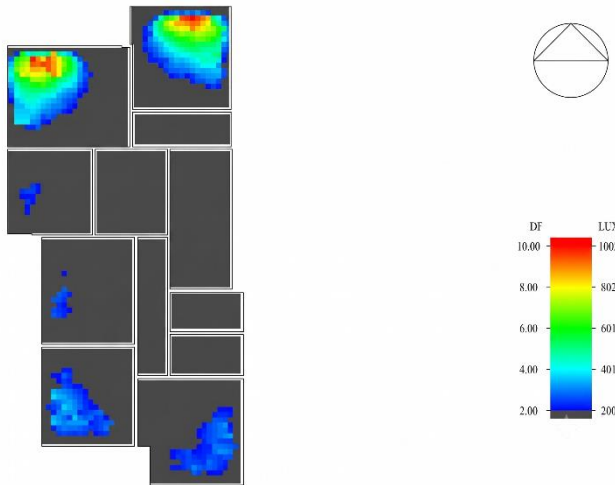


Fig. 9 The effect of all window size modifications on daylighting distribution: the proposed design

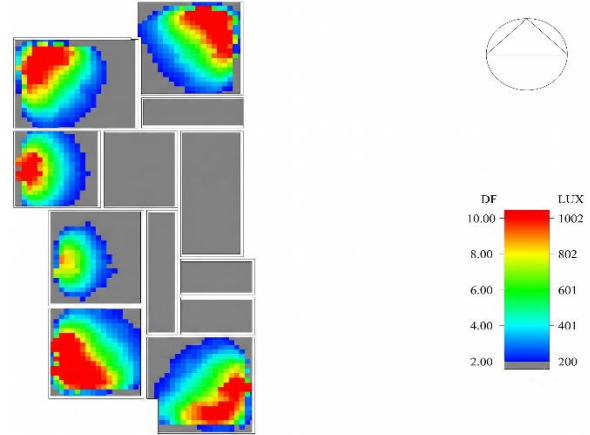


Fig. 10 The effect of window size on daylighting distribution: baseline model

4.1.4. Impact of Solar Shading Device on Energy Consumption (S4)

An overhang solar shading device was installed above the southern facades' openings to enhance the buildings' energy performance. Table 10 demonstrates that adding a shading device results in an 8.2% reduction in the cooling demand and design capacity. As such outcomes directly decrease the total building energy consumption from 6310.20 kWh/year to 6093.37 kWh/year, corresponding to a 3.44% reduction in energy consumption and its associated CO₂ emissions. Eventually, shading devices are an environmentally friendly intervention. Such findings are consistent with the results of Abu Qadourah's (2022) and Albadaineh's (2022) studies, affirming the positive impact of shading device designs on the buildings' energy performance [11, 12]. However, the present study further emphasizes the importance of determining the proper proportions of the overhang shading systems. The properties of shading systems represent an essential factor in increasing their effectiveness in minimizing the solar gain and distributing natural light.

Table 10. Impact of overhanging shading devices on energy consumption

Scenario	Heating capacity (kW)	Cooling capacity (kW)	Energy consumption (kWh/year)
S0	9.75	11.44	6310.20
S4	9.75	10.50	6093.37

4.1.5. Impact of Glazing Systems on Energy Consumption (S5)

In the baseline model, single glazing was used in windows. In the first alternative, when replacing single glazing with double glazing, the design heating and cooling capacities were reduced to 9.02 kW and 11.11 kW, respectively. Consequently, such findings lead to a 2.12% energy reduction. Improving the glazing layers enhances the energy performance. The triple-glazed case further decreased the heating and cooling capacities to 8.70 kW and 10.97 kW, respectively. Consequently, there is a 10.8% reduction in heating design capacity and a 4.1% reduction in cooling load,

resulting in an overall reduction of 3% in total energy usage, as depicted in Table 11.

Table 11. Impact of glazing types on energy consumption

Scenario	Heating capacity (kW)	Cooling capacity (kW)	Energy consumption (kWh/year)
S0	9.75	11.44	6310.20
S5a	9.02	11.11	6176.16
S5b	8.70	10.97	6120.79

As shown in Figure 11, upgrading the glazing from single to double and then triple glazing progressively reduced heating and cooling energy consumption, reducing CO₂ emissions accordingly.

This reduction resulted from the improved thermal performance of the glazing systems, which limited heat transfer. These findings align with previous studies, providing specific evidence for one-story houses in the suburban neighborhoods of Amman.

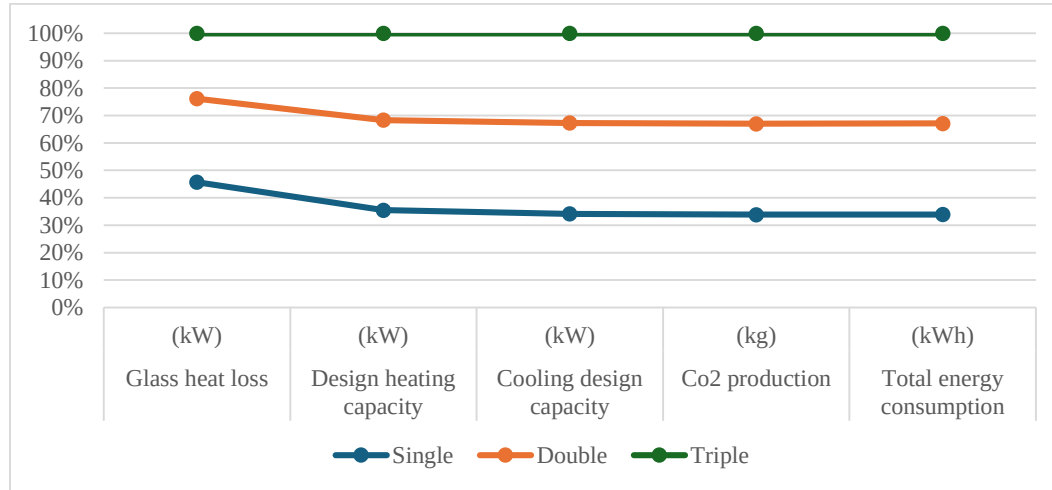


Fig. 11 Impact of glazed window types on energy performance

Such findings align with the previous studies; however, this study focused on the case of one-story houses in the suburban neighborhoods in Amman.

4.1.6. Impact of LED Lighting (S6) on Energy Consumption

Replacing the fluorescent lighting units with LED lamps decreased the energy consumption; thereby, improving the total energy performance, as shown in Table 12.

Table 12. Impact of using LED lighting on energy consumption

Scenario	Heating capacity (kW)	Cooling capacity (kW)	Energy Consumption (kWh/year)
S0	9.75	11.44	6310.20
S6	9.75	11.38	5940.45

The capacity of the heating system remained the same, at 9.75 kW, and the cooling system experienced a slight decrease in its design capacity, from 11.44 kW to 11.38 kW. However, the largest saving was achieved through reduced lighting electricity consumption, amounting to 369.75 kWh/year. These savings also reduced the environmental impact, lowering CO₂ emissions from 3813.12 kg to 3581.44 kg, representing a reduction of 6.1%. Additionally, the building's annual energy consumption decreased from 6310.20 kWh to 5940.45 kWh, which represents a 5.86% reduction, as shown in Figure 12. These findings demonstrate that selecting

appropriate lighting units is crucial for reducing electricity consumption in small single-story buildings.

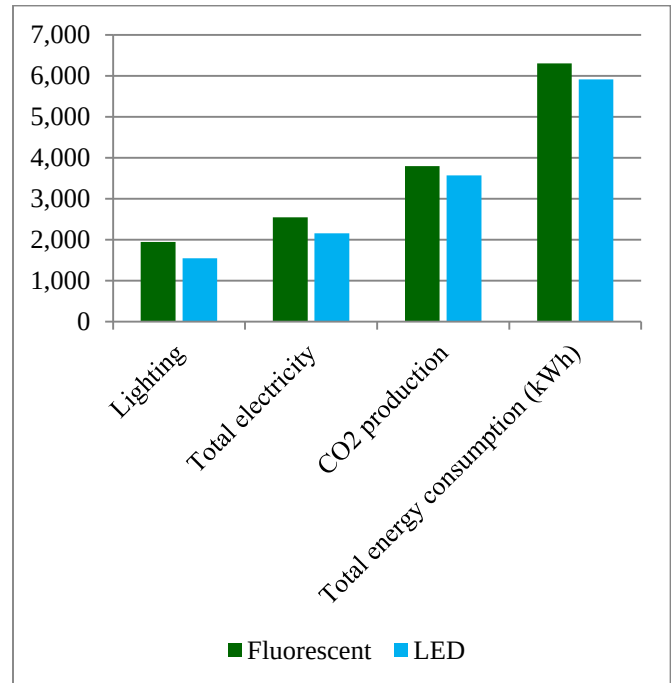


Fig. 12 Influence of lighting system type on energy consumption and CO₂ emissions

4.2. Development and Evaluation of the Optimal Retrofit Scenario

Each of the above-mentioned design interventions and retrofits' impact on energy performance was first examined independently. After that, the combined design scenario was produced by choosing the most optimal envelope parameters determined in previous sections, ensuring compliance with

local building codes. The recommended design entails the use of an overhang for shading, smaller window sizes on all facades, triple clear glazing rather than the existing single clear glazing, thickening of EPS insulation material in external walls from 50 mm to 80 mm, exterior roof coating, and switching from fluorescent lamps to LED lights, as shown in Table 13.

Table 13. Comparative effect of individual retrofit strategies on annual energy consumption

Scenario	Retrofit strategy	Energy Consumption(kWh/year)	Energy Saving (kWh)	Reduction (%)
S0	Baseline	6310.20	-	-
S1a	Green roof	6125.65	184.55	2.93
S1b	Reflective roof coating	5910.37	399.83	6.34
S2a	EPS 60 mm	6266.55	43.65	0.69
S2b	EPS 80 mm	6145.98	164.22	2.60
S3	Reduced WWR	5700.11	610.09	9.67
S4	Overhang shading	6093.37	216.83	3.44
S5a	Double glazing	6176.16	134.04	2.12
S5b	Triple glazing	6120.79	189.41	3
S6	LED lighting	5940.45	369.75	5.86

From the analysis results, it becomes clear that the studied retrofit strategies have different impacts on the building energy use per year. Among the retrofit actions, the largest reduction was achieved with the decrease of the window-to-wall ratio, which led to a 9.67% decrease in annual energy consumption. The relatively high sensitivity to the WWR is related to the contribution of windows to the process of solar

and conductive heat transfer. The reflective roof coating and LED lighting were responsible for the second- and third-largest decrease in energy use, at 6.34% and 5.86%, respectively. On the other hand, the increase in EPS insulation from 50 to 60 mm decreased the annual energy consumption by 0.69%, while the further increase in insulation to 80 mm increased the reduction to 2.60%, as shown in Figure 13.

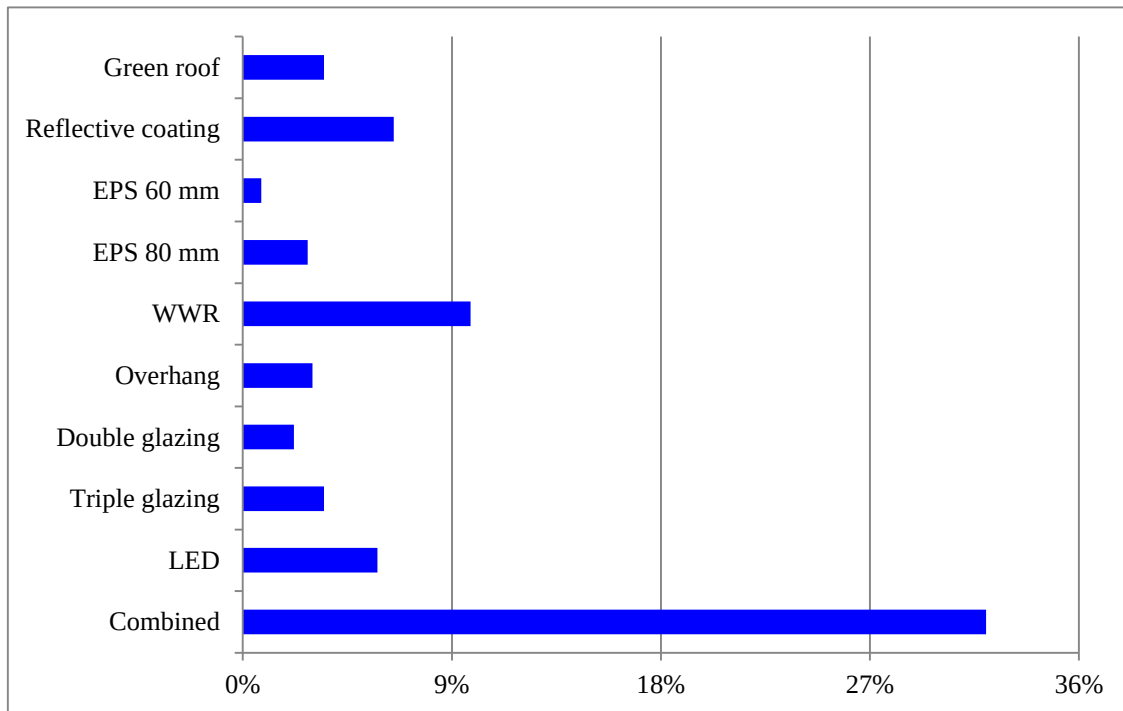


Fig. 13 Percentage energy consumption by intervention

The total annual energy consumption decreased from 6310.20 kWh/year to 4304.21 kWh/year, corresponding to an energy saving of 2005.99 kWh/year. Thus, securing an energy saving rate of about 31.8% when compared to the baseline

building model, as shown in Table 14 and Figure 14. It is clear from the above findings that the application of both passive techniques along with energy-saving lights can significantly save energy in residential buildings.

Table 14. A brief comparison between the baseline model and proposed optimum scenario

Type	Baseline model	Optimum scenario
Solar shading	No shading	Overhang shading device
WWR	20%	12%
Type of glass	Single clear glazing 6mm	Triple clear glazing 3mm Glaze, 6mm Air
External wall Construction layers	Limestone 50 mm Concrete 100 mm EPS 50 mm Hollow concrete 100 mm Plaster 25 mm	Limestone 50 mm Concrete 100 mm EPS 80 mm Hollow concrete 100 mm Plaster 25 mm
Roof construction layers	Tiles 30 mm Mortar 20 mm Reinforced concrete 100 mm Hollow concrete block 140 mm Plaster 25 mm	Reflective Coating 20 mm Tiles 30 mm Mortar 20 mm Reinforced concrete 100 mm Hollow concrete block 140 mm Plaster 25 mm
Lighting units'	Fluorescent	LED
Co2 production	3813.12 kg	3016.97 kg
Energy consumption	6310.20 kWh/year	4304.21 kWh/year
Energy saving %	0	31.8 %

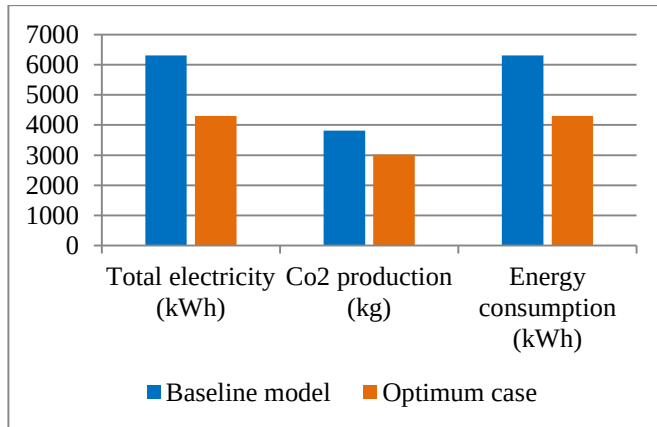


Fig. 14 Energy consumption comparison between the baseline model and the optimum one

Despite these positive energy-related results, decisions regarding which strategies to incorporate into existing building retrofits must also consider their indoor environment quality and economic implications. This highlights the need for multi-objective optimization techniques that account for both energy performance and cost-effectiveness. In the present research, WWR changes were introduced only for the southern façade because applying the same approach for all façades resulted in negative impacts on the daylight distribution inside the interior space as analyzed above. For this reason, the southern façade was chosen for WWR changes

to balance energy efficiency and the presence of sufficient daylight inside the building. This highlights the need to adopt multi-objective optimization techniques to consider both energy performance and cost-efficiency [6], while also accounting for indoor environmental quality. Accordingly, the section below presents an economic analysis of the proposed retrofit scenarios (S1 to S6).

4.2.1. Cost Analysis

According to the amount of energy saved per year derived from the simulation studies, an annual monetary value was calculated in accordance with the corresponding electricity tariffs applicable within the Jordanian context. Economic savings amounts for each measure was thus determined in Jordanian dinars. The cost of each one of the design intervention implementations was later quantified according to the local market prices in Jordan. The cost was determined based on two factors: the cost incurred from the implementation of the intervention during construction and the cost of incorporating the strategy into the building after construction. Thus, the present study provides recommendations for the existing building and/or the new ones. Both factors were calculated based on the variation between the initial cost and new strategy implementing cost. This helped in establishing the economic viability of each design intervention along with its contribution to reducing energy consumption.

Table 15 demonstrates how the cost values vary among the different design interventions. Modifying the WWR has the greatest annual savings at minimum construction phase costs and moderate post-construction costs. Installing LED lighting units contributes to lowering electricity use, thereby providing savings in electricity bill payments, and with low construction costs and lower replacement costs, it is therefore considered a cost-effective design intervention. Adding overhang shading devices offers a considerable energy-saving amount annually, with a relatively moderate cost. On the other hand, double and triple glazing reduce energy costs but are relatively expensive compared to some other alternatives, particularly where installation takes place after construction.

It also seems that green roofs provide effective savings per year; however, due to their higher costs, they might impact the economic feasibility of such projects. Therefore, reflecting exterior roof coating is more suitable strategy for one-story housing units (Dar). To summarize, these numbers demonstrate the total effect of the different techniques applied in improving the energy efficiency of the residential building and indicate the saving of 166.01 JOD Jordanian dinars annually on the electricity bill. Thus, it can be concluded that applying these design interventions during the construction phase is considered more cost-effective in comparison with postconstruction integration.

Table 15. Cost analysis

S	Retrofit Measure	During Construction (JD)	After Construction (JD)	Energy Saving (kWh/year)	Cost Saving (JD)
1	Green Roof	1950	7800	184.55	18.46
	Reflecting Coating	630	630	399.83	28.58
2	EPS 1 (60)	193	1600	43.65	4.37
	EPS 2 (80)	580	2164	111.22	11.12
3	WWR	-60	190	610.09	61.01
4	Shading Device	175	175	216.83	21.68
5	Double Glazing	250	900	134.04	13.40
	Triple Glazing	800	1400	189.41	18.94
6	LED Light	0	20	369.75	436.97

The overall savings amount in the total annual electricity costs resulted from the implementation of the optimized proposed design interventions and is approximately 166.01 JOD. Though this might seem relatively low, it still signifies a significant amount saved in annual energy consumption for ordinary one-story homes in suburban and rural areas in Amman. Consequently, any savings in annual electricity charges would help towards better financial sustainability for families. Therefore, the importance of this study lies in providing clear insight into how households should balance the use of both passive and active design methods of energy conservation.

4.2.2. Energy Performance of the Cost-efficient Scenario Simulation

Based on the economic evaluations of the individual retrofit interventions, a cost-informed combined scenario was developed. Unlike the energy-optimal scenario, which prioritised maximum energy reduction, this scenario incorporated interventions that provided a more practical balance between energy savings and implementation costs. It

included reflective roof coating, 60mm EPS wall insulation, a reduced WWR, fixed overhangs, double glazing and LED lighting, as presented in Table 15. When combined, these measures reduced annual energy consumption from 6310.20 to 5091.12 kWh/year with an annual energy savings of 1219.08 kWh/year, presenting 19.32% savings compared with the baseline building, as illustrated in Table 16.

Table 16. Energy and cost-efficient scenario

Scenario	Retrofit Measure	Baseline Specifications	Proposed Specification
S0	Reference Building	Existing configuration	Baseline model
S1	Roof Insulation	Conventional roof (U-value = 0.938 W/m ² K)	Roof insulation exterior coating (U-value = 0.397 W/m ² K)
S2	Walls	EPS = 50 mm	EPS = 60

	Insulation		mm
S3	WWR	20%	12%
S4	Solar Shading	No shading device	Fixed horizontal overhang
S5	Glazing Type	Single glazing (6 mm, $U = 6.121 \text{ W/m}^2\text{K}$)	Double glazing ($U = 2.761 \text{ W/m}^2\text{K}$)
S6	Lighting System	Fluorescent lamps	LED lighting
Total Energy Consumption		6310.20 kWh/year	5091.12 kWh/year

5. Comparative Context Studies

The results of this study show that the combination of passive envelope retrofitting methods with energy-efficient lighting greatly enhances the energy performance of one-story suburban residential buildings within the climatic conditions of Amman. Exterior wall insulation improvement, roof reflective surface, improved window to wall ratio, glazing improvement, exterior shading and lighting using LEDs helped to reduce the overall annual energy consumption by 31.8%. The outcomes include savings from 0.69% to 9.67% individually, while the combined approach resulted in savings of 31.8%. The absence of quantifiable data is regarded as one of the limitations of the research. Therefore, the findings were compared with the existing literature, revealing a consistency with other research showing the effect of passive design solutions on lowering energy consumption in hot-dry and Mediterranean climates.

The previous studies conducted in Jordan have stressed the importance of envelope improvement in saving energy consumption. For instance, Jaber et al. studied retrofitting solutions for existing residential buildings in Amman and concluded that an improvement of the thermal resistance through insulation of walls and windows would result to an energy savings of 22% [49]. Jarada and Ashhab estimated that improved materials of the envelope could save 24% of energy, while using efficient lighting and solar heaters could save about 39% of energy [50]. The current study saved 31.8%, which is comparable to the results obtained from previous studies.

The positive impact of the thermal insulation measures investigated in this study aligns with the findings of other studies in hot climate contexts. Umar and Asfour (2025) examined thermal insulation retrofits in a Saudi Arabia multi-story residential building and found that internal and external roof insulation and HVAC system upgrades save 65.5% of energy [51]. In this case, the energy saving achieved in the present study is less than their findings. This variation is due to the nature of retrofits that have been chosen (e.g., HVAC system upgrades) and the climatic conditions.

The significance of shading strategies highlighted in this study has been supported by similar findings within the context of Jordan. For example, Abbas et al. showed that natural ventilation and shading elements greatly enhanced the thermal performance of a multi-story residential building in Amman by lowering indoor temperature during daytime hours [52]. Likewise, Abu Qadourah et al. (2022) found that shading elements, along with insulation and ventilation, played an important role in minimizing the cooling load of multi-family residential buildings [11]. In the present study, the use of exterior shading helped minimize solar gain and cooling energy loads. The contribution of this study is lies in applying a scientific base for designing the shading device and highlighted the importance of installing the appropriate size and type.

Regarding glazing and windows alterations, earlier studies stressed the need to consider the window parameters to optimize the solar gains, daylight, and energy performance. The current study shows that reducing the window sizes and replacing single glazing with high-performance double or triple glazing reduce energy use and maintain daylight normal distribution. Such finding aligns with Ali et al. (2020) work which pointed out window parameters, shading systems, and insulation as important factors influencing energy performance in residential buildings in Jordan [17]. Unlike earlier studies which have mainly considered energy savings, this study has further considered the effect of the windows modification on daylight performance. The significance of this study lies in examining the influence of WWR on energy consumption while considering the daylight performance.

While the installation of a green roof would add additional resistance to heat loss and evaporation cooling effects, the use of reflective coating is an easier and more economical approach. This is especially so in the case of existing buildings. The contribution of the reflective roof coatings used in the current study is further corroborated from earlier studies carried out in hot climates [45]. Nonetheless, the current study initially considers the effect of the roof exterior coating on the energy consumption of a single-story residential building within the climate conditions of Amman. Moreover, the originality of this study lies in its integrated assessment of using the roof exterior coating as an energy-efficient approach for Amman, Jordan's climatic conditions. The present study findings also illustrate the significance of incorporating passive design with efficient lighting systems. The change from the use of traditional fluorescent bulbs to LED bulbs is among the elements that helped reduce energy consumption and CO₂ emissions. These findings support those by Jarada and Ashhab, which showed that efficient lighting systems alone can help save around 7% of energy in Jordanian domestic buildings [50].

In comparison with international research, the achieved energy saving is consistent with the results from the similar

integration of retrofit approaches. For example, Mousavi et al. revealed that a combination of insulation, reflective coating, Low-E glass, and shade can save energy up to 50% per year in Mexico [37]. Likewise, Mushtaha et al. reported an average saving of about 59% by employing an integrated approach of insulation, shading, and ventilation in residences in Gaza [28]. Such higher savings could be due to different climate conditions, building features, retrofitting measures, and modelling assumptions.

In particular, the present research contributes to the existing literature by overcoming some of the drawbacks of previous work. Previous research considered either one retrofit measure at a time or only multi-family buildings, while little is known about the effect of insulation, reflective roofs, shading, glazing system, window selection, daylighting, and lighting efficiency in combination in suburban single-story houses in Amman. Moreover, economic analysis of the retrofits was not sufficiently addressed in previous Jordanian literature. This research helps to make decisions by choosing effective retrofits in terms of saving energy and implementing those. Yet the extent of energy savings depends greatly on the climate, type of building, construction details, and choice of retrofit alterations.

The novelty in this study is reflected in the comprehensive evaluation of a number of retrofit options such as external solar shading, glazing windows retrofitting, walls' thermal insulation, reflective roof coating, and energy-saving LED lighting for suburban single-story residential buildings in the climatic environment of Amman, Jordan. Previous studies on energy consumption in buildings have either assessed the impacts of individual retrofit options, individual building systems, or multifamily residential buildings, but in the present case, the impacts of the above-mentioned retrofits alone as well as in combination are evaluated for the overall energy consumption. Also, daylighting and cost implications have been taken into account in the assessment, which makes the study more holistic than earlier efforts in the field.

It is worth noting that the performance of a building energy system depends not only on physical and technological factors but also on the behaviour of occupants and awareness of energy conservation techniques. In the context of Jordan, studies have revealed that socio-economic and behavioural factors are essential and should be considered in energy performance calculations. According to Jaber et al. (2025), economic constraints, awareness, and the readiness of individuals to spend on energy efficiency play a crucial role in making energy savings in low-income residential areas of Amman [53]. Similarly, Safaa Alwedyan, (2024) stated that the lack of awareness, economic constraints, and social support can create obstacles to energy savings [54]. Likewise, Albatayneh (2022) mentioned that cooling, water heating, refrigeration, and lighting contribute significantly towards household energy consumption in Jordan [35].

Further, there is recent evidence that supports the fact that adopting socio-technical perspective becomes necessary when analysing residential energy performance. In a study by Maaith and Sharmin (2026), it was revealed that factors related to behaviour of occupants and household attributes were responsible for explaining the variance in energy use compared to building attributes [55]. Hence, although simulation studies like the present study currently help in understanding the possible energy performance of retrofit measures in a controlled setting, it lacks the occupant behaviour and socio-economic analysis. Future studies can benefit from including field studies, surveys, and occupant questionnaires in order to understand how people use retrofitted buildings and how behaviours impact energy savings technically, socially, and economically.

Although the present study evaluates the operational energy performance of different retrofit strategies through dynamic annual simulations using DesignBuilder, it does not study does not consider the environmental impact of the embodied materials throughout their life cycles. Future studies should integrate Life Cycle Cost Assessment and Life Cycle Assessment with dynamic energy simulations to provide a more comprehensive sustainability evaluation of residential retrofit strategies in Jordan.

6. Conclusion

The current study conducts building energy simulation for a one-story residential building located in Amman. A baseline scenario was built using the DesignBuilder software under the climatic conditions of Mediterranean contexts. The objective of this study is to reduce the energy consumption of the building and enhance its thermal comfort level using retrofitting measures. Among the different proposed design interventions, the building envelope parameters, including walls, roof, and windows, contributes the most to the overall heat transmission, affecting heating and cooling requirements. Therefore, the insufficient thermal insulation of solar gains noticeably raises the annual energy consumption. In order to cope with such a challenge, right architectural design choices need to be made from the very beginning of construction phases.

Solar shading device installation, glazing performance improvement, wall insulation thickness, exterior roof coatings, and window size adjustments are all needed to decrease the cooling loads, electricity use, and their associated energy consumption. Furthermore, replacing fluorescent lighting with LED units significantly reduces electricity consumption. In the optimum design scenario, optimizing envelope parameters and incorporating energy-efficient lighting units decreases energy consumption by approximately 31.8%. Such findings contribute to improving the energy efficiency of one-story residential buildings within the Amman environment.

Although these interventions reduce operational energy consumption, many homeowners may be discouraged by their initial costs, especially in low- and middle-income households. Therefore, this study emphasizes the significance of the interconnection between energy efficiency of residential buildings and co-effectiveness in the process of making decisions at the stage of construction of the building's envelope or in the case of renovation of an existing building. The cost analysis proves that in addition to energy saving, it is necessary to consider the economic justification of retrofit measures. In addition, limited public awareness of long-term energy savings, insufficient technical expertise among contractors, and the absence of comprehensive financial support mechanisms may further hinder the large-scale adoption of energy-efficient retrofit technologies. Consequently, successful implementation requires an integrated policy framework that combines financial incentives, stronger regulatory enforcement, public awareness campaigns, and professional training programs for architects, engineers, and contractors. Such measures would facilitate the wider adoption of energy-efficient retrofit strategies, reduce household electricity consumption, and contribute to Jordan's national energy-efficiency and carbon-reduction objectives. Energy saving policies should be formulated both locally and nationally in order to optimize its efficiency [6]. Awareness campaigns, environmental education, and targeted assistance for energy-poor households financial support are needed to promote sustainable energy-saving behavior in Jordan [56]. According to the findings of this research, policy makers are advised to adopt financial schemes to encourage the use of passive retrofit techniques which include roof coating, improved window design, use of external shading, and LED lighting.

Furthermore, strengthening the enforcement of Jordanian energy-efficiency regulations and raising the awareness of how important is to integrate mandatory envelope performance requirements into residential building codes would support the widespread implementation of such measures. The results obtained from the study are beneficial to energy households, architects and policymakers to have a clear picture of the current status of one-story houses within the suburbs of Amman. The present study calls for encouraging collaboration among governmental authorities, building owners, designers, and other relevant stakeholders.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Ethical Approval

This study is analytical and involves no human or animal subjects.

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Author Contribution

RA and BG prepared the manuscript, and SA reviewed the manuscript.

Data Availability

The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

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