

## Article

# Applying Passive House Design in a Hot–Arid Climate—Adoption Assessment and Energy Performance Simulation: Case of Riyadh, Saudi Arabia

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## Abstract

Energy consumption in hot–arid and warm climates is driven by cooling demand during long, intense summers. In these contexts, the residential sector accounts for much of national electricity use, and cooling can exceed 70% of annual household consumption. Saudi Arabia exemplifies this pattern, with the residential sector consuming over half of the national electricity and cooling dominating demand in hot–arid cities like Riyadh. Against this background, this study explores the adaptation of the Passive House approach—originally developed in cold and temperate regions—for a cooling-dominated, hot–arid context. A detached villa in Riyadh was selected as a case study, and its energy performance was modeled in DesignBuilder using a baseline calibrated against 12 months of electricity bills. Passive House measures were then tested. The results showed that insulating walls and roofs provided the largest reductions in electricity use, at 21% and 15%, respectively, while high-performance glazing with external shading achieved an additional 3.4%. Improvements in airtightness and ventilation with heat recovery yielded only minor savings in a cooling-dominated climate. When all measures were implemented together, the villa's annual electricity consumption was reduced by 48% compared with the baseline, and cooling demand was reduced by 72.3%. These findings demonstrate that Passive House measures can be effectively adapted to hot–arid conditions, with envelope insulation and solar-gain control delivering the most significant benefits. The Riyadh case underscores the potential of Passive House principles to reduce residential electricity use in cooling-dominated housing and to support energy-efficient design in hot–arid and warm-climate regions.

**Keywords:** passive house; hot–arid climate; cooling; energy-efficiency; simulation

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## 1. Introduction

One of the most urgent global challenges today is rising energy consumption, particularly in the building sector, which is responsible for a major share of electricity use and carbon emissions [1]. Electricity consumption in residential buildings has significantly increased as a result of ongoing population growth and urbanization processes [2]. This continued growth in residential electricity demand underscores the urgent need to adopt energy-efficient building practices to alleviate pressure on national energy resources and

infrastructure. In this context, improving the energy performance of buildings is not only an environmental priority but also an economic necessity, especially in rapidly developing, hot-climate countries. Given this context, the building sector has become a primary focus of global and national energy-efficiency initiatives. Buildings currently account for nearly one-third of global electricity consumption [3], driven mainly by cooling, heating, and lighting demands, which reinforces the critical need for adopting energy-efficient design strategies [4].

To address these growing challenges in the building sector, energy-efficient building design has emerged as a critical solution to reduce electricity demand and improve long-term building performance. One of the most recognized international design frameworks in this field is the Passive House standard. Developed in Germany in the early 1990s, Passive House emphasizes five core principles: high thermal insulation, airtight construction, thermal bridge elimination, high-performance windows, and mechanical ventilation with heat recovery [5]. When applied effectively, these strategies can reduce a building's heating demand by up to 90% compared to traditional construction methods, while maintaining superior indoor comfort and durability [6].

In hot and arid regions, the need for high-performance and energy-efficient buildings is particularly urgent. These regions are characterized by very high summer temperatures and extended cooling seasons, resulting in a heavy reliance on mechanical air conditioning. In many hot-climate countries, the residential sector accounts for a substantial portion of national electricity demand due to the dominance of cooling loads, and this reliance on mechanical air-conditioning is particularly pronounced in cities such as Riyadh, Saudi Arabia [7,8]. Despite this, a large share of the housing stock is constructed with inadequate insulation, high air infiltration rates, and inefficient envelope materials, which contribute to high energy consumption and poor thermal performance [9]. These conditions underscore the necessity of adapting global energy-efficiency frameworks, such as the Passive House standard, to the specific realities of hot-arid, cooling-dominated climates.

While several international studies have demonstrated the effectiveness of Passive House principles in cold and temperate climates, there is a notable lack of empirical research exploring their feasibility and performance in extremely hot regions [10,11]. The limited evidence for hot-arid and other warm climates constrains the generalizability of Passive House design guidelines and creates uncertainty regarding which of its principles offer the most effective energy savings in cooling-dominated contexts. This research gap is particularly relevant for rapidly developing, energy-intensive regions in need of substantial reductions in residential electricity use.

Therefore, this study aims to evaluate the applicability of Passive House to hot-arid, cooling-dominated residential buildings through a simulation-based case study. The case study building is modeled in DesignBuilder, with a baseline model calibrated using 12 months of measured electricity-consumption data. The analysis quantifies the energy-saving potential of the five Passive House principles. It discusses their contribution to national energy-efficiency targets and long-term strategies for reducing residential electricity demand in hot-arid climates. Previous Gulf studies have either evaluated a complete Passive House design as an integrated whole [12], or assessed selected envelope or system measures, in several cases reporting cooling rather than whole-building savings [13–17]. The novelty of this work lies in combining, in a single case study, an existing occupied villa, a baseline calibrated against twelve consecutive months of measured electricity bills, and the complete five-principle Passive House package, with the principal measures quantified both individually and together—an integrated and calibrated assessment not previously reported for a hot-arid Gulf villa.

## 2. Literature Review

### 2.1. Energy-Efficient Buildings

Energy-efficient buildings have become a central priority in global sustainability efforts over the past decades. They have been widely adopted in Europe and other developed regions, with the primary aim of reducing energy consumption and associated emissions [1]. A building is considered energy-efficient when it can achieve the required indoor comfort conditions with the lowest possible energy input compared to a conventional baseline [18]. However, the adoption of energy-efficient design practices in developing and hot-arid regions remain comparatively limited due to climatic, economic, and regulatory constraints [19]. The extreme climatic conditions, combined with economic and regulatory barriers, hinder the direct application of strategies developed for heating-dominated climates [20]. Most existing evidence originates from cold and temperate regions, which makes direct transfer difficult and underscores the need for climate-specific adaptation [21]. Therefore, climate-responsive approaches are essential for achieving effective energy reductions in these regions [21].

In the context of building energy-performance simulation, previous research has shown that energy use in buildings is shaped by several interrelated factors, including the characteristics of the building envelope and its thermal properties such as insulation, glazing, and roof design; the indoor and operational conditions related to comfort settings and internal heat gains; and the efficiency of building systems such as air-conditioning, ventilation, and lighting. These aspects together define the overall energy behavior of a building and form the basis for performance-based design approaches [22,23]. The Passive House standard builds directly on these principles, integrating envelope efficiency, mechanical systems, and indoor comfort within a single, cohesive framework aimed at minimizing energy demand [24].

### 2.2. Passive House and Its Adaptation in Hot-Arid Climates

The Passive House standard is an internationally recognized design methodology that enhances energy efficiency, comfort, affordability, and ecological sustainability in buildings. Passive house buildings have been shown to reduce heating demand by up to 90% in cold and temperate regions [25], while their potential in cooling-dominated hot-arid climates depend primarily on reducing solar and conductive heat gains [24]. The core criteria established by the Passive House Institute (PHI) include a maximum heating demand of 15 kWh/m<sup>2</sup>-year, an airtightness level of  $n_{50} \leq 0.6 \text{ h}^{-1}$  at 50 Pa [5], with adjustments in warm climates to account for cooling demand [24].

Rather than relying on a single measure, the Passive House approach functions through a set of integrated principles that collectively minimize unwanted heat transfer and ensure stable indoor conditions. High-performance insulation reduces conductive heat flow through walls and roofs. Similarly, airtight construction limits uncontrolled infiltration. High-performance glazing with low U-values and climate-appropriate Solar Heat Gain Coefficient (SHGC) reduces solar and conductive gains. Thermal-bridge-free detailing enhances overall envelope efficiency by preventing localized heat-flow pathways that undermine insulation performance [26]. Finally, balanced mechanical ventilation with heat recovery (HRV) maintains indoor air quality, tempers the air supply, and continuously replaces stale indoor air with fresh conditioned air, thereby supporting comfort and reducing ventilation-related energy losses [27].

Although these principles have been extensively validated in cold and temperate regions, their overall evaluation in hot-arid climates has been insufficiently studied [28]. As a result, the overall effectiveness of the complete Passive House approach in such environments remains unclear. A few studies have been carried out in hot climates, with much

of the available evidence concentrated in European contexts [26,29,30]. Nevertheless, the underlying philosophy—reducing unwanted heat transfer and providing controlled, low-energy ventilation—remains applicable across diverse climates [24]. In hot and warm climates, research on Passive House performance remains limited [29,31], particularly in hot-arid regions where existing studies mainly address individual measures rather than a complete, integrated Passive House package [32,33].

In hot and warm regions, the priority of design shifts from reducing heating demand to mitigating cooling and latent loads [34], while maintaining indoor comfort and air quality. Achieving this balance requires climate-specific performance targets, envelope systems designed to limit conductive and solar gains, and ventilation strategies that incorporate heat or enthalpy recovery with seasonal bypass options.

Within these climates, where mechanical cooling becomes the primary driver of electricity use [35], opaque assemblies (walls and roofs) are prioritized for very low U-values through continuous insulation and thermal-bridge-free detailing; this directly suppresses sensible gains and flattens cooling peaks [36], which is a critical priority in hot-arid climates where elevated outdoor temperatures persist for long periods [37]. In parallel, fenestration must limit solar transmittance via low-SHGC glazing, thermally broken frames, warm-edge spacers, and meticulous airtight installation, while external fixed shading (e.g., louvers/overhangs) trims beam radiation on critical orientations [34,38]. This is particularly important because solar gains through glazing can significantly increase cooling loads in highly sun-exposed regions [23,33,39].

High airtightness remains essential to stabilize indoor conditions and make ventilation intentional rather than leak-driven; together with a robust envelope, it reduces uncontrolled sensible/latent loads and enables right-sized HVAC in cooling-dominated buildings—even though the relative energy impact of tighter envelopes is smaller than in heating climates [24]. Studies show that leakage—often concentrated at junctions and interfaces can notably increase cooling demand in hot-arid climates [30,40]. Ventilation should be balanced and continuous with heat/enthalpy recovery. HRV is appropriate in hot-arid contexts, whereas energy recovery ventilation (ERV) benefits hot-humid climates by limiting moisture ingress; a summer bypass and demand-controlled airflow help avoid over-conditioning during milder hours [38]. Because outdoor-indoor temperature differentials are high for extended periods, thermal bridges at slab edges, columns, lintels, and window perimeters can dominate local heat flux and surface temperatures. Adapting Passive House concept to warm climates requires appropriate envelope strategies that limit heat gains and support consistent indoor performance [24].

In addition to envelope enhancements, passive design in hot climates also relies on optimizing building orientation and form. Studies have shown that appropriate building positioning and orientation can significantly reduce energy demand [31]. Furthermore, the strategic use of locally available materials, such as rockwool, not only improves insulation performance but also reduces the embodied carbon of construction. Cool roofs with high thermal emittance and solar reflectance [41]—are another essential technique, as they minimize absorbed solar heat and radiate excess energy, decreasing rooftop temperature and lowering cooling loads [41].

Consistent with the warm-climate literature, previous simulations for residential buildings in hot-arid regions have indicated that envelope measures tend to dominate whole-house energy savings, with glazing and shading providing additional but more moderate benefits, and airtightness delivering smaller yet still relevant contributions in cooling-dominated conditions [9]. Existing reviews note that only a few Passive House studies have been carried out in predominantly warm climates, and only a small number of case studies have examined full Passive House applications in hot climates compared with the extensive work in cold and temperate Europe [12,42]. Taken together, these find-

ings highlight a fragmented, largely measure-by-measure evidence base for Passive House strategies in hot and warm climates, with limited empirical assessment of fully integrated design packages under cooling-dominated conditions. This research gap is particularly critical in hot-climate countries where space-cooling needs strongly shape electricity demand; Saudi Arabia is a prominent example, motivating the more detailed examination of national building energy consumption presented in the following section.

### *2.3. Building Energy Consumption in Saudi Arabia*

The building stock in Saudi Arabia consumes the majority of nationally generated electricity, and residential buildings account for around 50% of total building-stock electricity use, underscoring the centrality of residential buildings in national demand profiles [43]. Within Saudi homes, Air Conditioning (AC) dominates end-use electricity, with stock-level modelling estimating that AC was responsible for about 66% of residential electricity consumption in 2018 [35]. This pattern is not unique to Saudi Arabia; rather, it reflects a broader trend across hot-climate countries where residential cooling represents one of the largest and fastest-growing electricity end-uses [44].

This cooling dominance aligns with system-level evidence, where hourly generation rises steeply with temperature, with 1.177 GW of additional capacity brought online for each 1 °C increase when moving from winter to summer conditions [45]. This reflects the strong sensitivity of electricity demand to temperature in cooling-dominated systems, underscoring the importance of improving building envelope performance [46].

The residential energy challenge in Saudi Arabia is compounded by the widespread use of thermally inefficient construction—uninsulated walls, single glazing, high infiltration rates—and a rapid pace of urban development [43]. In such climates, low-rise detached houses with weak thermal envelopes experience notably higher cooling loads and peak electricity demand [47,48]. Between 2007 and 2018, residential electricity consumption in Saudi Arabia increased by 45% [49], reflecting an increasing reliance on mechanical cooling.

Given this context, implementing advanced building-performance strategies is essential to reduce cooling loads and enhance residential energy efficiency. The Passive House approach offers a practical pathway to reduce cooling demand and improve overall residential energy performance.

## **3. Methodology**

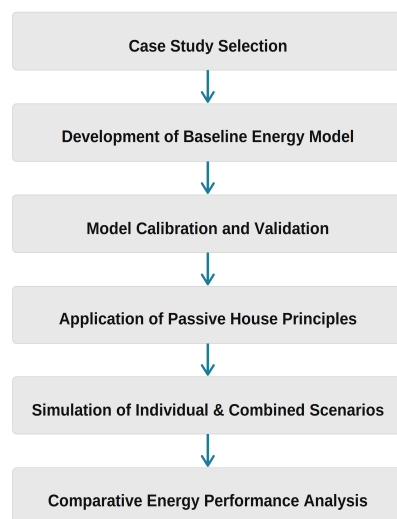
### *3.1. Research Design*

This study adopts a simulation-based research design to evaluate the impact of implementing Passive House principles on the energy performance of a real residential villa located in Riyadh, Saudi Arabia. A representative case study building was first selected, and a detailed 3D energy model was developed in DesignBuilder 7.3.1.003 based on the architectural drawings and construction specifications of the villa.

The methodology comprised three main simulation phases. In the first phase, a baseline energy model of the existing villa was created using as-built geometry, material properties, internal loads, and local climatic data. In the second phase, the baseline model was calibrated and validated against 12 consecutive months of measured electricity bills to improve the accuracy and credibility of the simulation results.

In the third phase, Passive House improvements were applied to the calibrated model, including enhanced insulation, improved airtightness, high-performance glazing, thermal-bridge mitigation, and the integration of mechanical ventilation with heat recovery. In this phase, both the calibrated baseline model and the Passive House-enhanced model were analyzed under identical boundary conditions, and each Passive House meas-

ure was also simulated separately. This made it possible to quantify the individual and combined contributions of Passive House strategies to electricity-use reduction under the climatic conditions. The overall research process is illustrated in Figure 1, which summarizes the main steps of the simulation methodology.



**Figure 1.** Flowchart of the research methodology.

### 3.2. Case Study Building

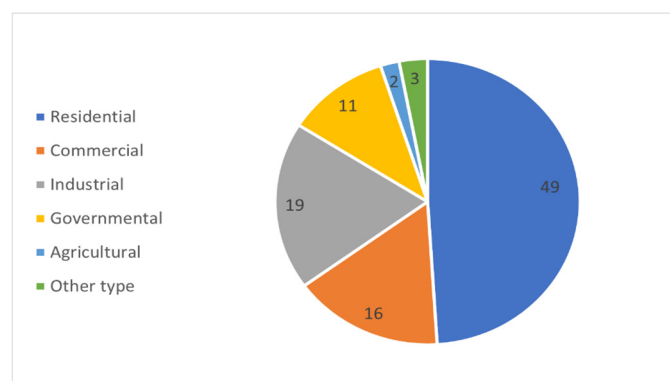
Riyadh was selected as the location for this study due to its strategic significance, climatic conditions, and its role in national sustainability goals serving as a representative testbed for adapting the Passive House standard to hot-arid environments. Over recent decades, the city has experienced rapid urban expansion and an intensive construction boom, with its built-up urban area increasing by about 90% between 1990 and 2009 and its urban clusters more than doubling again by 2022. These characteristics make Riyadh suitable for examining Passive House adaptation under hot-arid conditions.

In addition, Riyadh experiences some of the highest peak electricity loads in the country, mainly due to the extensive use of air conditioning in residential buildings during prolonged summer periods. These conditions emphasize the urgency of implementing energy-efficient design approaches such as the Passive House standard. Riyadh is also a central focus in national transformation programs such as Saudi Vision 2030, which promotes enhanced energy performance and sustainability in the built environment.

The residential building category was selected because it represents the largest share of electricity consumption in Saudi Arabia, accounting for more than 50% of the total national electricity use. Among residential typologies, detached villas are the most dominant housing type, especially in suburban areas like Riyadh, where land availability and privacy are prioritized. This dominance of the detached villa is not confined to Saudi Arabia: a region-wide archetype study of all six GCC countries identifies the villa as the predominant residential typology across the Gulf, attributing its prevalence to the demand for privacy, space for large families, and design customization [50]. The studied villa is therefore representative of the prevailing detached typology found throughout the hot-arid Gulf region rather than an atypical national case. These buildings are typically constructed using thermally inefficient techniques, such as uninsulated cement block walls, single-glazed windows, and poor airtightness, which significantly increase cooling loads.

As shown in Figure 2, the residential sector accounts for the largest share of electricity consumption in Saudi Arabia, at 49%, indicating strong potential for energy savings

through strategies such as Passive House design. Given this high share of electricity use, the residential sector represents a priority target for energy-efficiency interventions.



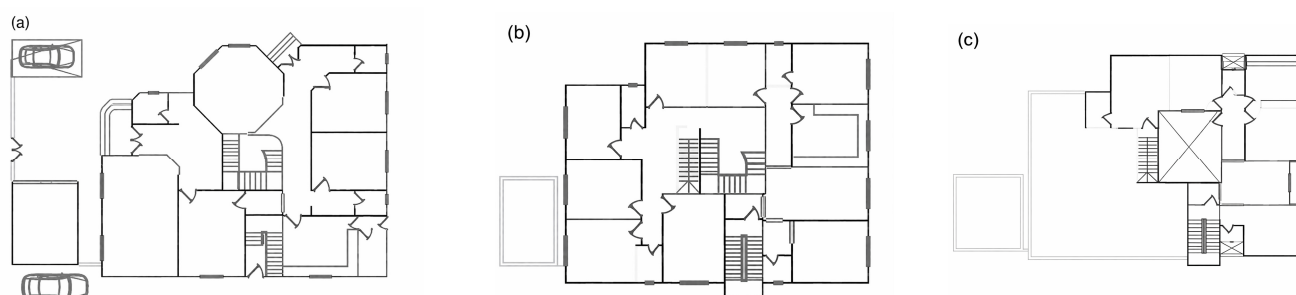
**Figure 2.** Sectoral distribution of electricity consumption in Saudi Arabia.

The case study is a detached residential villa located in the Al-Yassmen neighborhood in Riyadh, Saudi Arabia. The building comprises two main floors, an upper annex, and a basement level used for services. It is designed for single-family residential use. The main façade of the building faces the northwest, and the structure is surrounded by other residential buildings on three sides, with setbacks of approximately two meters.

The total built-up area is 756.97 m<sup>2</sup>, distributed across four levels. The architectural drawings presented in Figure 3 include detailed floor plans and elevations, which were used to create the 3D simulation model in DesignBuilder. These drawings were referenced to ensure accurate dimensions, zoning, and spatial configurations in the simulation. The distribution of the built-up area by floor is summarized in Table 1.

**Table 1.** Built-up area distribution by floor.

| Floor          | Area (m <sup>2</sup> ) |
|----------------|------------------------|
| Ground Floor   | 275.48                 |
| First Floor    | 315.13                 |
| Upper Annex    | 136.33                 |
| Basement Annex | 30.03                  |
| Total Area     | 756.97                 |



**Figure 3.** Architectural floor plans of the case-study villa: (a) ground floor, (b) first floor, (c) upper annex.

### 3.3. Baseline Modeling and Configuration

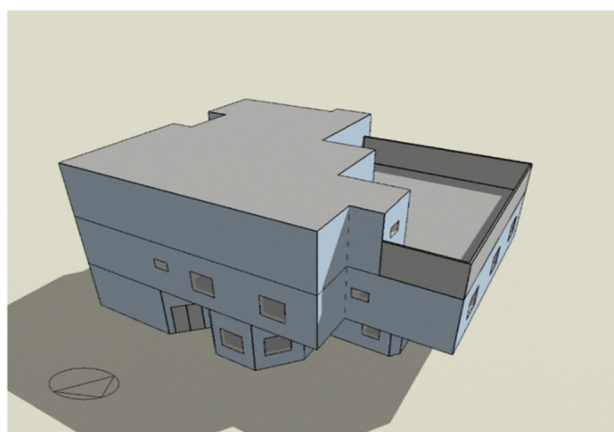
To evaluate the building's performance and simulate the impact of Passive House design improvements, a comprehensive energy model was developed using DesignBuilder. This modeling process aimed to quantify the impact of Passive House principles

on energy consumption and thermal comfort in a hot climate context. Two simulation stages were conducted: the baseline model, representing the villa's existing configuration, and the improved Passive House model applying Passive House principles.

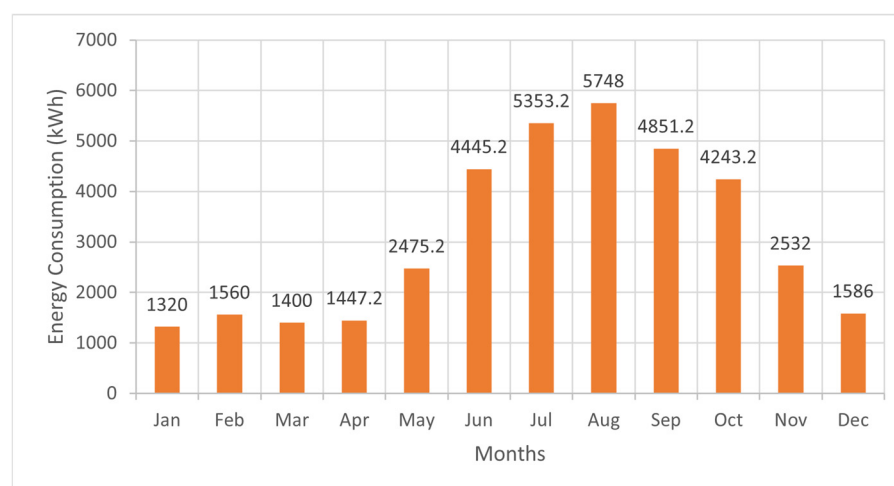
The methodology involved creating a detailed 3D representation of the building, incorporating architectural geometry, construction materials, occupancy schedules, internal gains, lighting, and HVAC systems based on design specifications and relevant standards. Climate data was sourced from the nearest weather station to ensure realistic environmental conditions. Zoning was applied according to thermal and functional spaces to accurately simulate internal loads and control strategies (see Appendix A for zoning layout). A detailed 3D representation of the villa was developed using DesignBuilder to support the baseline energy simulation, as shown in Figure 4.

The model was calibrated using benchmark values or operational data where available, and simulations were performed to assess annual energy use, peak loads, and thermal comfort performance. The results informed the optimization of building elements for improved energy efficiency.

Monthly electricity bills for the case study villa, covering a full calendar year, were collected and used as a reference for evaluating the energy performance of the baseline model. These real-world consumption records were used to assess the alignment between simulated and actual energy use, particularly with respect to seasonal trends and total annual demand. Figure 5, presents the measured monthly electricity consumption of the villa, based on utility bills for one operational year.



**Figure 4.** 3D model of the case study villa developed in DesignBuilder for baseline energy simulation.



**Figure 5.** Measured monthly electricity consumption of the case study, used for validation.

The villa was partitioned into thermal zones according to the function of each space, and consistent activity, lighting, and equipment templates were applied across zones of the same type. Each space, including bedrooms, living rooms and Majlis (traditional reception rooms), dining areas, kitchens, bathrooms, toilets, and circulation spaces) was linked to a standard residential activity template provided in DesignBuilder, so that the same occupancy, lighting, and equipment values were applied to all spaces of the same type across the three floors. Service and unconditioned spaces, such as the stairwell and basement, were treated as unoccupied.

The lighting and equipment values listed in Table 2 represent nominal rated power densities ( $\text{W/m}^2$ ) used as model inputs rather than fixed annual internal gains. In EnergyPlus, actual internal gains are calculated dynamically by applying the relevant operating schedule fractions to occupancy, lighting, and equipment loads for each zone throughout the year. With these schedules applied, the resulting annual internal gains were 4740 kWh from lighting and 7918 kWh from equipment, reflecting intermittent operation rather than continuous full-load use.

Thermostat control applied occupied setpoints together with setback temperatures during unoccupied periods. In the conditioned habitable spaces, an occupied cooling setpoint of 25 °C and a heating setpoint of 18 °C were used (the heating setpoint was raised to 21 °C in living rooms and Majlis), with setback temperatures of 28 °C for cooling and 12 °C for heating. Circulation and transitional spaces used a cooling setpoint of 23 °C with a 26 °C setback. The occupancy densities, internal gains, and setpoint logic adopted for each zone type are summarized in Table 2.

**Table 2.** Zone-level activity templates and operational input parameters used in the DesignBuilder model.

| Activity Template (Zone Type)           | Occupancy Density (People/m <sup>2</sup> ) | Lighting (W/m <sup>2</sup> ) | Equipment (W/m <sup>2</sup> ) | Cooling Setpoint/Setback (°C) | Heating Setpoint/Setback (°C) |
|-----------------------------------------|--------------------------------------------|------------------------------|-------------------------------|-------------------------------|-------------------------------|
| Domestic Bedroom                        | 0.0229                                     | 2.30                         | 3.58                          | 25/28                         | 18/12                         |
| Domestic Lounge (living rooms & Majlis) | 0.0188                                     | 2.30                         | 3.90                          | 25/28                         | 21/12                         |
| Domestic Dining room                    | 0.0169                                     | 2.30                         | 3.06                          | 25/28                         | 18/12                         |
| Domestic Kitchen                        | 0.0237                                     | 2.30                         | 30.28                         | 25/28                         | 18/12                         |
| Domestic Bathroom                       | 0.0187                                     | 2.30                         | 1.67                          | 25/28                         | 18/12                         |
| Domestic Toilet                         | 0.0243                                     | 2.30                         | 1.61                          | 25/28                         | 18/12                         |
| Common circulation areas                | 0.0115                                     | 2.30                         | —                             | 23/26                         | 18/12                         |

“—” indicates that no equipment load was assigned.

The internal gains were defined using the standard residential activity templates available in DesignBuilder. A metabolic factor of 0.90 was applied, and the equipment radiant fraction was set to 0.20. Common circulation areas, including corridors, the entrance area, and stairs, were assigned no equipment load. Based on these assumptions, the model produced annual internal heat gains of 4740 kWh from lighting and 7918 kWh from equipment.

In the DesignBuilder model, the construction template incorporates specific materials assigned to key building elements to reflect the thermal characteristics of the design, as summarized in Table 3.

**Table 3.** Summary of key building envelope and system inputs used in the energy model.

| Building Element       | Material Name                                                     | Thickness |
|------------------------|-------------------------------------------------------------------|-----------|
| External Walls         | Cement Block                                                      | 20 cm     |
| Facade Cladding        | Limestone                                                         | 3 cm      |
| Internal Partitions    | Cement Block                                                      | 20 cm     |
| Flat Roof              | Reinforced Concrete (Hordi Roofs)                                 | 32 cm     |
| Floor Slab (Raft)      | Reinforced Concrete                                               | 50 cm     |
| Floor Insulation Layer | Thermal Insulation (Polystyrene)                                  | 6 cm      |
| Floor Screed Layer     | Cement Mortar                                                     | 3 cm      |
| Floor Finishing        | Ceramic Tiles                                                     | 1 cm      |
| Windows                | Aluminum Windows (Two/Single Panels & Wings)                      | N/A       |
| Doors                  | Wrought Iron + Wood (Interior & Exterior)                         | N/A       |
| Weather File           | Riyadh, Saudi Arabia                                              | N/A       |
| Lighting Load          | 2.30 W/m <sup>2</sup>                                             | N/A       |
| HVAC System            | Split with fresh air (Simple HVAC); DX cooling, seasonal COP 3.85 | N/A       |

The external and internal walls were modelled using Cement Wall (External) and Cement Wall (Internal) constructions, providing consistent thermal resistance and structural integrity. The flat roof was defined using Reinforced Concrete, a typical system for structural and thermal efficiency in residential buildings. All floor elements, including ground, external, and internal floors, were specified as Reinforced Concrete, ensuring uniform thermal mass and load-bearing capacity throughout the building envelope. These material definitions play a crucial role in the accuracy of the thermal performance simulation.

The baseline model employs individual split-unit air conditioners assigned to each occupied room, with a rated seasonal Coefficient of Performance (COP) of 3.85 for cooling. No central ducted system is modelled, consistent with the predominant installation practice for residential villas in Riyadh. Each zone's conditioning is controlled independently by the thermostat setpoints described above (25 °C cooling and 18 °C heating in habitable rooms, with 23 °C cooling in circulation spaces), with setback logic applied during unoccupied periods. The system was represented using the "Split with fresh air" template in DesignBuilder, with mechanical fresh air supplied at the minimum rate defined on a per-person and per-area basis from the activity template; no heat recovery is present in the baseline. A domestic hot water (DHW) system with an efficiency of 0.85 was also included to meet hot-water demand. In the Passive House scenario, the same split-system cooling is retained and complemented by balanced mechanical ventilation with sensible heat recovery, as detailed in Section 3.4.

### 3.4. Passive House Design Improvements

This study applies the five Passive House principles as climate-adapted design strategies rather than as a PHI standard-compliance assessment [29]. The PHI-related envelope and airtightness specifications described below are reported as relevant performance indicators within the scope of the simulation model, rather than PHPP-based demand or primary-energy verification; the airtightness value, in particular, is a modelling target and not a measured blower-door result.

To enhance the energy performance of the baseline building model, several passive and active design improvements were incorporated and analyzed using DesignBuilder. The modifications began with the thermal envelope, where external walls were upgraded with additional insulation, reducing their U-value to 0.15 W/m<sup>2</sup>K, significantly improving their resistance to heat loss. Similarly, the roof was insulated using 125 mm of extruded polystyrene (XPS), which led to a substantial decrease in its U-value, thereby reducing

heat gains and losses through the roof. No insulation was added to the floors, keeping their thermal characteristics unchanged, which allowed for assessing the impact of other envelope elements in isolation.

In terms of airtightness, the infiltration rate was improved from the base rate to 0.6 air changes per hour (ACH) at 50 Pa, minimizing uncontrolled air leakage and enhancing thermal stability within the indoor environment. High-performance windows were also introduced, characterized by a U-value of 1.0 W/m<sup>2</sup>K and a SHGC of 0.3, which not only improved insulation but also reduced unwanted solar gains. To further mitigate solar heat gains and glare, fixed external shading devices (0.5 m louvers) were added, providing passive solar control without compromising daylight access.

On the systems side, the split-system cooling of the baseline was retained at an essentially unchanged seasonal efficiency (COP 3.85) and was complemented by balanced mechanical ventilation incorporating a sensible heat-recovery unit, modelled within the “Split with fresh air” template in DesignBuilder. The heat-recovery unit was assigned a sensible effectiveness of 0.70, applied to the mechanical fresh-air stream defined on a per-person and per-area basis, with no economizer (free-cooling) bypass enabled. As the cooling COP was held essentially unchanged from the baseline, the modelled system-side saving (−2.06%) is attributable to sensible heat recovery on the ventilation air rather than to higher cooling-equipment efficiency, which is consistent with the limited role of ventilation heat recovery in cooling-dominated climates. The domestic hot water (DHW) system was upgraded in the Passive House scenario to a more efficient configuration ( $\eta = 0.9$ , compared with 0.85 in the baseline). These combined envelopes and system-level upgrades form a comprehensive retrofit strategy aimed at lowering overall energy consumption and maintaining the intended indoor setpoints.

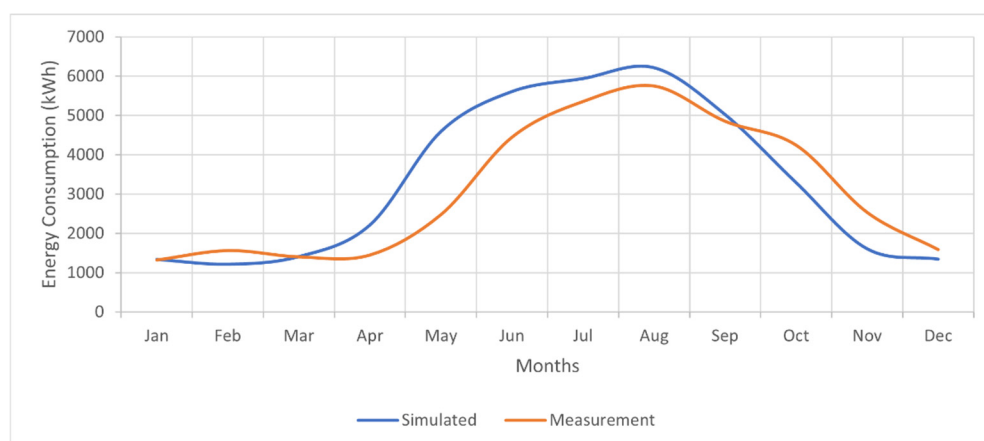
### 3.5. Model Validation

To ensure the reliability of the simulation outputs, the baseline model was validated against actual electricity consumption records collected from utility bills covering a year. Building energy simulations are generally regarded as reliable when the predicted annual consumption does not deviate by more than  $\pm 10\%$  from actual measured values. The simulated annual electricity consumption was 39,799.6 kWh, while the measured consumption was 36,961.2 kWh, which corresponds to a relative deviation of 7.68%. The reported deviation in the current study is closely aligned with the results reported by [51,52]. Therefore, the obtained deviation falls within the acceptable range, which confirms that the baseline model is sufficiently calibrated and can be used for further scenario analysis. As shown in Figure 6, both trends demonstrate close alignment across the year.

The baseline model was calibrated against the measured utility bills by adjusting a set of operational input parameters within realistic, documentation-based ranges until the simulated annual consumption closely matched the measured data. The principal parameters refined during this process were: (i) the occupancy and operation schedules, which were defined on a room-by-room basis to reflect the actual use of each space; (ii) the lighting power density, which was specified following ASHRAE guidelines; and (iii) the HVAC operation, where conditioning was disabled in non-conditioned service spaces such as bathrooms. The envelope thermal properties (wall, roof, and floor U-values) and the air-infiltration rate (0.70 ach) were retained from the building documentation. A month-by-month comparison of the measured and simulated electricity consumption is presented in Table 4.

These results demonstrate that the developed energy model adequately replicates the operational energy demand of the case study in Riyadh and can be reliably used to assess the impact of Passive House design strategies. Overall, the comparison results show that the consumption trend in both measured and simulated data is quite similar and that there

is a reasonable agreement between the simulated results predicted by DesignBuilder and the actual consumption from utility bills. The validation processes were primarily used to check the model calculations and provide a sense of certainty and confidence in the simulations to conduct a study and analysis of Passive House interventions under Saudi climatic conditions. The model can therefore simulate the actual performance and conditions of the selected case study.



**Figure 6.** Comparison of simulated and measured monthly electricity consumption for the case study.

**Table 4.** Monthly comparison of measured and simulated electricity consumption for the baseline model.

| Month                   | Measured (kWh)  | Simulated (kWh) |
|-------------------------|-----------------|-----------------|
| January                 | 1320.0          | 1334.9          |
| February                | 1560.0          | 1213.1          |
| March                   | 1400.0          | 1408.1          |
| April                   | 1447.2          | 2213.0          |
| May                     | 2475.2          | 4594.9          |
| June                    | 4445.2          | 5611.4          |
| July                    | 5353.2          | 5941.2          |
| August                  | 5748.0          | 6217.1          |
| September               | 4851.2          | 5023.7          |
| October                 | 4243.2          | 3292.0          |
| November                | 2532.0          | 1606.7          |
| December                | 1586.0          | 1343.7          |
| <b>Total</b>            | <b>36,961.2</b> | <b>39,799.6</b> |
| <b>Annual deviation</b> |                 | <b>7.68%</b>    |

Minor month-to-month differences between the measured and simulated values arise mainly from the billing cycle not aligning exactly with calendar months, the use of fixed operational schedules, and possible occupant-behavior variations during the summer months, such as changes in cooling operation, thermostat adjustments, and room-use patterns. As the model was calibrated at the annual level, these differences do not affect the validity of the baseline for the comparative scenario analysis.

## 4. Results

### 4.1. Baseline Energy Performance

The baseline simulation of the villa indicates an annual electricity consumption of 39,799.6 kWh, reflecting the strong climatic influence of the hot-dry environment. Energy

use is clearly concentrated in the summer season, when outdoor air temperatures frequently exceed 45 °C. During the four hottest months (May–August), the villa consumed 22,364.7 kWh, representing 56.2% of the annual total. Within this period, monthly demand averaged 5591.2 kWh, with a maximum of 6217.1 kWh in August. By comparison, the winter months (January–February) averaged only 1274.0 kWh, showing the dominance of cooling loads. The August peak is nearly five times the winter baseline.

Intermediate, or “shoulder,” months exhibit transitional patterns. For example, April (2213.0 kWh) and October (3292.0 kWh) stand between winter lows and summer peaks, while September (5023.7 kWh) still reflects heavy cooling demand. Collectively, these months account for 37.4% of annual consumption, whereas the winter period contributes just 6.4%.

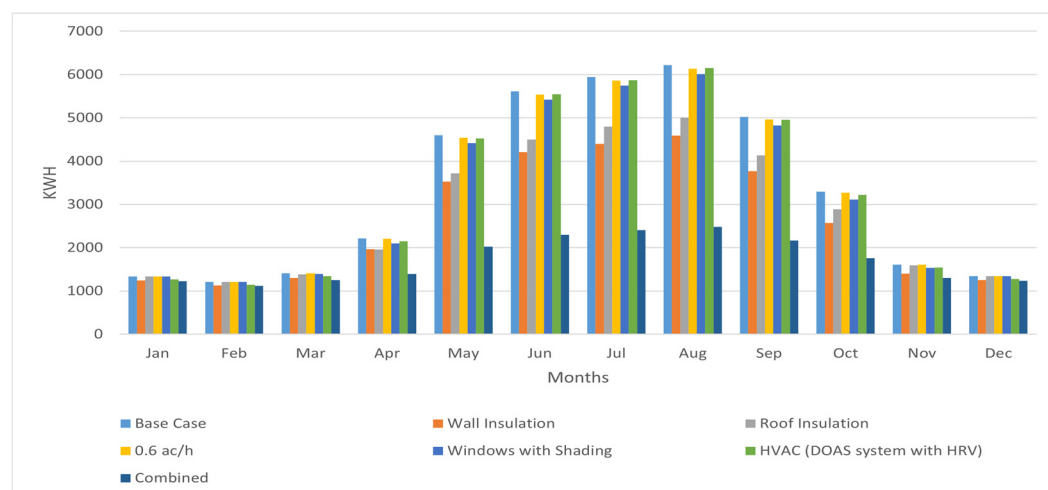
This seasonal distribution underlines the villa’s dependence on mechanical cooling, with consumption rising sharply from late spring, peaking during midsummer, and declining as outdoor temperatures ease in autumn. The baseline profile thus establishes the critical importance of cooling reduction strategies in the subsequent analysis, particularly those targeting thermal insulation, solar control, and HVAC efficiency—the primary drivers of household electricity demand in Saudi Arabia’s residential sector [7].

#### 4.2. Impact of Passive House Improvements

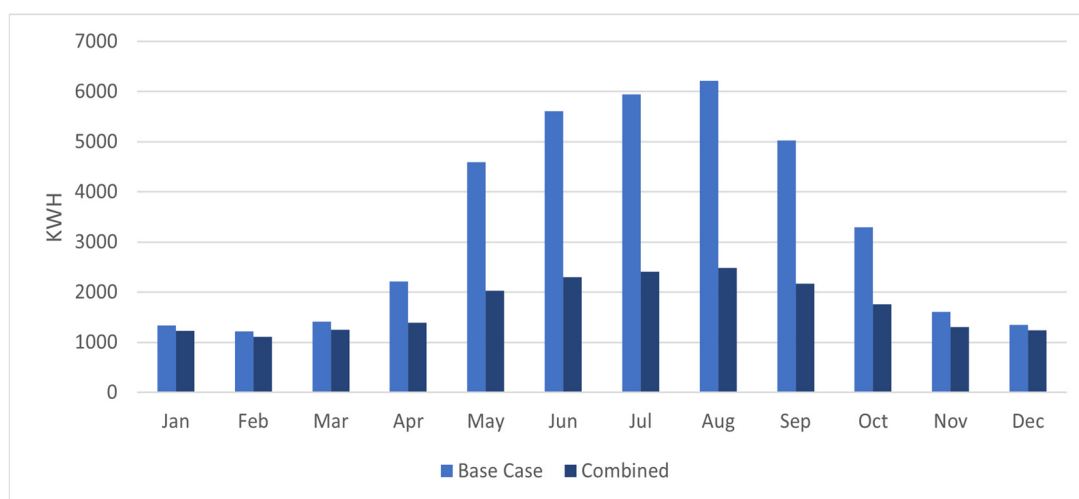
Applying Passive House principles resulted in substantial reductions in the villa’s annual electricity consumption compared to the baseline (39,799.6 kWh). Among the individual measures, wall insulation achieved the largest savings, lowering demand to 31,354.2 kWh (−21.2%), followed by roof insulation at 33,868.7 kWh (−14.9%). In contrast, improving airtightness (0.6 ACH) and upgrading the HVAC system had only minor impacts (−0.95% and −2.06%, respectively). The introduction of windows with shading achieved a moderate reduction of −3.41%.

When all measures were applied in combination as a full Passive House package, the villa’s annual consumption fell to 20,650.503 kWh, representing a 48.11% reduction relative to the baseline. These results highlight the dominant role of envelope improvements (walls and roofs) in driving performance gains, while also demonstrating the cumulative benefit of integrating multiple Passive House principles as illustrated in Figure 7.

Seasonal differences are also apparent in the combined scenario, where the largest reductions coincide with the summer cooling season. Peak consumption in August was reduced by more than 40% compared with the baseline, while June and July achieved comparable monthly savings. In cooler months, the absolute reductions were smaller due to the lower baseline demand, yet Passive House measures still deliver consistent savings across the entire year. This confirms the suitability of Passive House strategies in hot–arid climates, where cooling is the main factor shaping residential electricity use, as shown in Figure 8.



**Figure 7.** Annual electricity consumption of the baseline and Passive House improvement scenarios.



**Figure 8.** Monthly electricity consumption of the case-study villa for the baseline and combined Passive House.

#### 4.3. End-Use Breakdown of Electricity Consumption

To complement the scenario-level comparison presented in Section 4.2, the simulation results were further disaggregated into end-use categories, namely lighting, room electricity, cooling, and domestic hot water (DHW).

Figure 9, reports the annual consumption in each category for both the baseline and the Passive House scenario. In addition, Table 5 summarizes the relative contribution of each end-use in the baseline case and Passive House strategy scenarios.

The results demonstrate that cooling is the dominant end-use in the baseline scenario, with an annual consumption of 24,005.5 kWh, representing 60.3% of the total demand (39,799.6 kWh). After applying Passive House measures, cooling demand decreased to 6640.1 kWh, representing a 72.3% reduction and therefore providing the largest share of total energy savings. In contrast, lighting and room electricity decreased only slightly (−5.2% and −6.3%, respectively), while DHW consumption decreased by 15.0%. The DHW reduction is mainly attributable to the improved efficiency of the hot-water equipment itself, rather than any Passive House-specific intervention, consistent with evidence that the use of energy-efficient water heaters directly reduces DHW energy consumption [53].

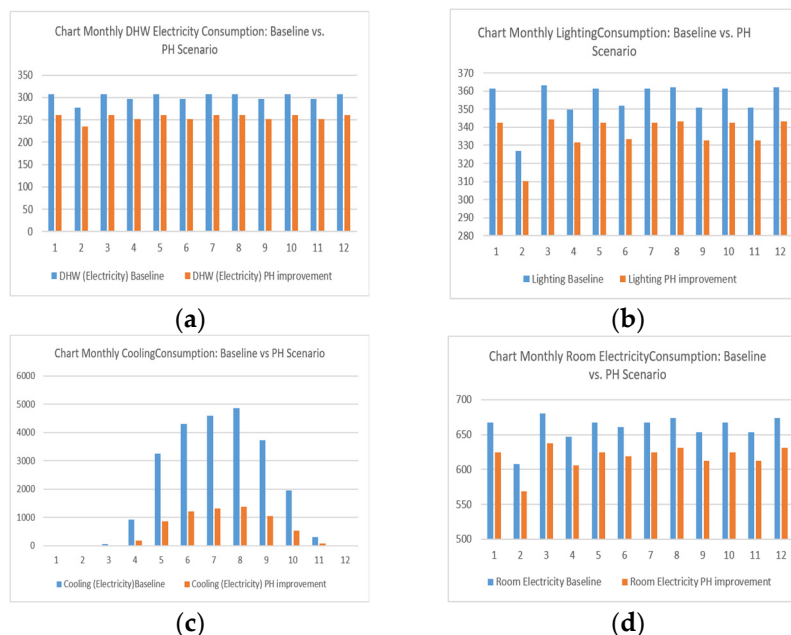
The monthly profiles reveal that cooling loads peak in August (4874.2 kWh) and July (4606.2 kWh) under the baseline, but are reduced to 1386.5 kWh and 1308.4 kWh, respectively, in the Passive House scenario as shown in Figure 9. By comparison, lighting, room

electricity, and DHW remain relatively stable across the year, with only minor variations between baseline and Passive House conditions.

The distribution of annual electricity consumption is further illustrated in Table 5.

Where the relative reduction achieved in each end-use is reported: cooling decreased by 72.3%, DHW by 15.0%, room electricity by 6.3%, and lighting by 5.2%. This confirms that cooling is by far the principal driver of residential electricity demand in Riyadh's hot-dry climate and highlights the critical role of building envelope improvements in reducing cooling requirements.

As with all simulation-based studies, the results presented here are subject to a number of inherent uncertainties that should be considered when interpreting the findings. Occupant behavior, including thermostat adjustments and actual usage patterns, was represented through fixed schedules and design setpoints; such simplifications are a recognized source of discrepancy between simulated and measured energy consumption in residential buildings [17]. The baseline infiltration rate was derived from typical construction practice rather than direct measurement; variations in this parameter can meaningfully influence modelled cooling-energy outcomes in hot-arid residential buildings [54]. Material thermal properties were assigned from construction specifications and published values; uncertainty in as-built envelope performance is a known limitation of simulation input data, particularly in older buildings [45]. Although a formal sensitivity analysis of these parameters was beyond the scope of the present work, the ranking of individual measures and the direction of the findings are consistent with patterns reported across the regional literature, ref. [54] providing reasonable confidence that the principal conclusions are likely to remain broadly stable under moderate variations in the input assumptions described above.



**Figure 9.** Monthly end-use electricity consumption for the baseline and Passive House scenarios, shown separately for (a) domestic hot water (DHW), (b) lighting, (c) cooling, and (d) room electricity.

**Table 5.** End-use breakdown of annual electricity consumption (kWh) for the baseline and Passive House improvement scenario.

| End-Use Category | Baseline (kWh) | Passive House Scenario (kWh) | Reduction (%) |
|------------------|----------------|------------------------------|---------------|
| Room Electricity | 7918.3         | 7417.7                       | 6.3%          |
| Lighting         | 4263.5         | 4041.7                       | 5.2%          |

|         |          |        |       |
|---------|----------|--------|-------|
| Cooling | 24,005.5 | 6640.1 | 72.3% |
| DHW     | 3610.9   | 3068.1 | 15.0% |

## 5. Discussion

In this study, the full Passive House package cut annual electricity use by 48.11% relative to the baseline. Specifically, the annual cooling load was reduced by 72.3%. The ranking of individual measures—walls and roof first, windows with external shading next, and HVAC/airtightness upgrades last—aligns with what the literature reports for buildings in a hot–arid climate. Furthermore, regional simulations show that passive envelope strategies—better constructions, optimized glazing, and shading—deliver substantial cooling-energy reductions under present and future climates [7].

At the monthly scale, the results in this study exhibit a distinctly seasonal profile with the most considerable absolute reductions occurring in the summer-peak months (June–August). In contrast, winter shows more minor absolute changes due to inherently lower cooling needs. This pattern is consistent with Riyadh’s extended hot season—roughly mid-May through late September—when average daytime highs reach 39–43 °C, and July is typically the hottest month [55], and with the AC-centric load profile of Saudi households, where air-conditioning accounts for about 65–70% of residential electricity use [43]. Accordingly, load-reduction measures naturally deliver their largest savings during the summer peak, and the concentration of monthly savings in this period is fully expected for Saudi homes, where summer demand often far exceeds winter levels [56]. Moreover, this overall magnitude of reduction is consistent with results from hot–arid contexts, yet it contrasts with findings in temperate or cold-climate Passive House studies, where airtightness and heat-recovery ventilation often account for a larger share of the savings [57].

These seasonal patterns highlight the importance of climate context when evaluating Passive House performance. Therefore, unlike cold-climate Passive House cases where heating dominates energy demand, cross-climate evidence consistently shows large Passive House gains, but the dominant end-use varies by climate. In cold/temperate Europe, Passive House projects routinely report 80–90% reductions in heating demand attributed to airtightness and heat-recovery ventilation coupled with high envelope performance [24]. In hot–arid contexts like Saudi Arabia, the literature pivots to cooling-energy reduction, highlighting envelope upgrades and solar-gain control as first-order levers for detached homes. Recent simulations on a typical Saudi detached house show substantial cooling cuts under present and future climates when constructions, glazing, and shading are optimized [9]. Moreover, component-level analysis in the same study further confirms the significant role of insulation, especially roof insulation, in reducing cooling loads, with 60% reduction in cooling load [9].

The 48.1% reduction in whole-house electricity is substantial and fully consistent with hot–arid evidence, especially since many Gulf studies report cooling-only savings [13,14], whereas this study reports reductions in total electricity across all end-uses. In other words, the observed reduction reflects broader energy savings beyond cooling energy alone, aligning with the envelope and solar-control emphasis documented for Saudi villas. This strong agreement reinforces the robustness of the simulation results and highlights the relevance of adopting a comprehensive retrofit package rather than isolated measures.

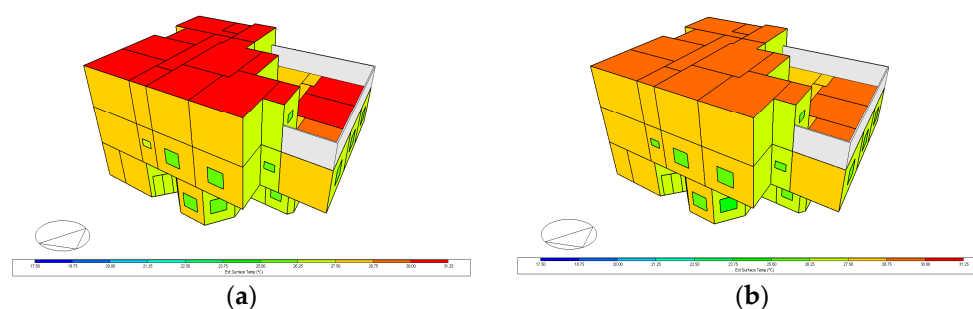
In summary, relative to heating-led European Passive House outcomes, Riyadh’s cooling-led context naturally expresses savings in a different way; the result demonstrates a substantial reduction that is consistent with prior hot–arid evidence, while reinforcing the primacy of envelope and solar-gain measures identified in the regional literature. The following sections therefore evaluate how each individual measure contributed to this overall outcome.

### 5.1. Opaque Envelope (Walls and Roof)

In hot-arid climate, cooling loads are dominated by two physical pathways, conductive heat transfer through opaque elements and solar gains at windows. Measures that block conduction (low-U roof/wall assemblies) and limit solar gains (low-SHGC glazing with fixed external shading) therefore produce the largest overall reductions in cooling energy for hot-arid residences, as repeatedly observed in simulation studies and component-level diagnostics [7].

In this climate, the building's exterior envelope is the primary pathway for unwanted heat gains; therefore, enhancing its thermal resistance delivers the greatest energy saving [9]. Among the individual passive measures, enhancing opaque envelope components (walls and roof) yielded the greatest reduction in energy consumption by 21% (to 31,354.2 kWh) while roof insulation achieved 15% (to 33,868.7 kWh) relative to the 39,799.6 kWh baseline. This pattern aligns with regional evidence from Gulf countries, which shows that improving wall and roof insulation consistently lowers residential cooling demand [15]. Further confirmation outcome was reported by [12], which found that upgrading the building fabric in such climates reduced overall energy demand by about 20% and cooling demand by nearly 50%. Together, these findings reinforce wall and roof insulation as a primary retrofit priority for conduction-driven cooling environments.

This effect is illustrated in Figure 10 which compares the external surface temperatures of the villa before and after applying roof insulation. Under baseline conditions, the roof appears predominantly in red, indicating surface temperatures exceeding 31 °C and substantial heat accumulation. Following the application of insulation, these areas shift to orange and yellow tones, demonstrating a clear reduction in surface temperature and heat transfer into conditioned spaces. Because the roof receives the highest cumulative solar exposure throughout the year, enhancing its insulation and applying high-reflectance cool-roof finishes plays a critical role in suppressing heat gains. Optimization studies in hot-arid climates report significant cooling-energy reductions when roof thermal properties are improved [41], while regional case studies show 12–33% savings from roof-focused upgrades in hot-arid settings [7], reinforcing the strategic importance of the roof in hot-arid residential retrofits.



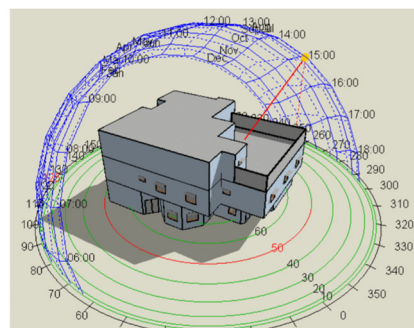
**Figure 10.** Comparison of external surface temperatures before (a) and after (b) roof insulation.

Building-performance investigations in hot-dry regions consistently highlight envelope insulation as a decisive efficiency lever, an emphasis reflected in prevailing regional design practices. Simulation studies from comparable climates indicate that upgrading wall and roof insulation commonly achieves 15–30% reductions in cooling electricity use [14]. This coherence between regulatory guidance and quantified performance further validates fabric-first strategies as both climatically appropriate and practically feasible for retrofitting cooling-dominated housing. Overall, these findings confirm that enhancing

wall and roof insulation should be the first retrofit priority in hot-arid climates, as it delivers the most substantial reductions in cooling-energy demand [9].

### 5.2. Windows and Shading

As illustrated in Figure 11, limiting solar gains at windows is also important in hot regions, as lower-SHGC glazing and fixed external devices materially reduce cooling demand [34]. In the villa case, the use of high-performance glazing combined with a fixed external shading device (0.5 m) reduced total annual electricity consumption by 3.42%. Although this reduction is smaller than that achieved by wall and roof insulation, it still highlights the added value of solar-control strategies in hot-arid housing. This outcome reflects their role in reducing transmitted solar radiation during peak summer loads. These findings emphasize that transparent elements, though smaller in impact, complement the overall envelope strategy by targeting solar-gain pathways rather than conductive pathways.



**Figure 11.** Solar path analysis for the case-study villa in Riyadh, illustrating annual sun exposure patterns.

The relatively modest impact is directly linked to the villa's low window-to-wall ratio (WWR), which was approximately 4.9%, constrains the overall contribution of fenestration improvements. Similar observations were reported in Saudi Arabia, for example, ref. [58] tested multiple window and shading configurations in Riyadh and found that high-performance glazing achieved around 4.8% savings on average, while fixed overhangs contributed about 3.9%. Ref. [59] similarly observed minimal differences in energy reduction at low WWRs (5–15%), confirming that the impact of fenestration measures remains limited when window areas are small. These results are consistent with the 3.42% reduction obtained in this case study, confirming that while glazing and shading strategies provide measurable benefits, their influence remains limited under hot-arid conditions with relatively small fenestration areas. Likewise, ref. [34] demonstrated that well-designed external shading can meaningfully reduce solar heat gains and improve indoor comfort in hot-climate buildings.

In summary, windows and shading deliver secondary but meaningful savings that complement the dominant contribution of the opaque envelope, particularly in villas with low WWR, such as the present case. More broadly, regional evidence indicates that high-performance glazing coupled with effective external shading yields moderate but meaningful reductions by tempering solar gains—an effect repeatedly emphasized in hot-climate reviews in the Gulf Cooperation Council (GCC) case studies [60].

The findings of this study relate to a single detached villa, but the five Passive House principles are not specific to this building type. They apply to other residential forms as well, even if the relative weight of each principle shifts from one type to another. What drives this shift is mainly the building geometry and its systems: the ratio of exposed envelope to volume, the roof-to-floor ratio, the WWR, the compactness of the form, its ori-

entation, and the HVAC configuration. These factors set the balance between conductive heat gains through the opaque surfaces and solar gain through the glazing [61,62]. In multi-family blocks and high-rise buildings, the roof covers only the top floor, and the exposed envelope per unit volume is smaller. Roof and wall insulation; therefore, contribute less, while glazing and shading carry more weight as the WWR grows [54,62]. Compact and attached forms of this kind have been linked to lower cooling demand in hot-dry contexts [62]. The villa studied here lies at the lower end of the WWR range, therefore, the opaque envelope accounts for most of the observed energy savings, as confirmed by the present study. Smaller or more exposed villas tend to have a higher envelope-to-volume ratio, which would push the opaque envelope into an even larger role, whereas larger villas, especially those with higher WWRs, would rely more on glazing and shading [16].

### 5.3. Airtightness

The observed reduction in annual electricity consumption of 0.95% resulting from airtightness improvements in this study aligns with findings from other hot-arid regions, where infiltration typically contributes only a minor share of cooling loads. For instance, a UAE case study experimentally assessed six different window sealing strategies in a residential building and found that, despite noticeable improvements in airtightness verified through blower-door and infrared imaging techniques, the overall reduction in cooling energy use was limited to about 3% [17]. While improving airtightness plays a role in stabilizing indoor environments and supporting mechanical ventilation systems, its direct contribution to cooling energy savings remains modest compared to passive measures like thermal insulation and solar-control glazing [63]. Similar outcomes have been documented in other hot-climate residences, where reductions following leakage control were relatively small [63].

In hot climates dominated by solar radiation and internal gains, infiltration accounts for a relatively small portion of total cooling demand. Tightening air infiltration typically produces smaller relative savings in cooling-dominated climates than in heating-dominated ones; studies report infiltration impacts of 4–14% on cooling energy versus 13–30% on heating [64]. This limited influence is largely climate-dependent as Airtightness—crucial in heating-led climates—tends to yield comparatively modest additional savings under cooling-dominated conditions, with simulation evidence showing that cooling energy is minimally influenced by tighter envelopes relative to heating energy [65]. Similarly, a study in China found that reducing ACH lowers both heating and cooling loads, with a greater impact on heating demand [66]. This highlights the climate-dependency of airtightness effectiveness, with limited returns expected in hot-arid regions. This highlights that airtightness provides only secondary benefits in hot-arid regions, where cooling loads are driven mainly by solar and conductive heat gains rather than infiltration [67]. In the present Passive House adaptation for Riyadh, airtightness is best understood as a supporting measure that enables controlled mechanical ventilation, rather than as a primary driver of large cooling-energy savings.

### 5.4. Mechanical Ventilation

In this study, the integration of a balanced mechanical ventilation system with sensible heat recovery (HRV) produced a modest improvement of approximately 2% in annual electricity consumption compared to the baseline split-unit configuration. This relatively small improvement reflects that the baseline system was already highly efficient ( $COP \approx 3.8\text{--}4$ ), leaving limited potential for additional savings through ventilation heat recovery. Consistent with previous studies, HRV systems typically achieve 5–7% gross energy savings; however, when fan power is included, the net gain often falls to approximately 1% [68]. In contrast, savings are noticeably larger in older, lower-efficiency villas and become

smaller—or even negative, when the baseline Energy Efficiency Ratio (EER) is already high [35]. For example, ref. [69] analyzed existing villas with low-efficiency split units ( $\text{COP} \approx 1.5$ ) and showed that upgrading to higher-efficiency systems produced substantial electricity savings, demonstrating that the greatest relative benefits arise when baseline equipment efficiency is low.

Within the Passive House framework, balanced mechanical ventilation with heat recovery is essential for safeguarding indoor air quality (IAQ) and enabling controlled, continuous ventilation [29]. In warm-to-hot climates, HRV provides supplementary energy benefits while primarily supporting IAQ [70]. Moreover, Passive House strategies must be climate-adapted to avoid adverse effects. In hot regions, excessive insulation and airtightness without proper ventilation can lead to overheating, elevated humidity, and degraded IAQ [70]. Ultimately, as has been succinctly noted, the main purpose of mechanical ventilation is to achieve acceptable IAQ [71]. Accordingly, in cooling-dominated climates where cooling systems already operate efficiently, HVAC plays a complementary role by ensuring IAQ, supporting airtightness, and delivering incremental reductions in cooling demand consistent with Passive House adaptation in hot-arid environments.

The results of this study demonstrate that the Passive House framework can deliver substantial reductions in residential electricity use in hot-arid, cooling-dominated contexts when its strategies are properly climate-adapted, which aligns with evidence from warm climates such as the hot-humid regions where Passive House projects have also achieved noticeable demand reductions [38]. Importantly, no single Passive House measure independently transforms performance in hot-arid regions; rather, only their integration yields cumulative benefits that are both technically robust and practically achievable. The largest benefit arises when the principles are deployed as an integrated package rather than as isolated retrofits, reflecting well-documented synergies among insulation, glazing/shading, airtightness, thermal-bridge control, and balanced ventilation in whole-building optimization [20,72]. Such an integrative approach maximizes energy savings while supporting the practical applicability of Passive House design within hot-arid climate conditions.

### *5.5. Limitations, Generalizability, and Future Research*

Several limitations should be considered. First, the analysis is based on a single detached villa in Riyadh modelled under one present-day weather file; although calibration against twelve months of measured bills (7.68% deviation) and corroboration with regional studies support the ranking of measures, the findings are most reliable as a guide to measure prioritization in similar hot-arid villas with low WWR rather than as universal values, and the reported percentages should not be transferred directly to other typologies, areas, or cities. Second, no cost-benefit or life-cycle cost analysis was undertaken; CAPEX, maintenance, tariffs, payback, and NPV were outside the scope, and because tariff structures and energy-price assumptions strongly affect payback periods [47,73], the energy-based ranking should not be read as an economic ranking; cost and incentive barriers are themselves recognized obstacles to Passive House adoption in the hot-arid context [13]. Third, occupant behaviors were represented through fixed schedules and set-points, so adaptive actions such as window opening, thermostat adjustment, and intermittent room use were not dynamically modelled—a recognized source of simulation-reality divergence [17]. Fourth, only a current weather file was used; future-climate scenarios were not simulated, although projected warming raises cooling demand and may increase the relative importance of envelope measures [9,74]. These boundaries mean the policy and economic implications are directional rather than prescriptive: the results can inform envelope-first discussions in residential energy-code development but do not establish optimal insulation thicknesses, cost-justified incentives, or guaranteed future per-

formance. Future work should extend this calibrated framework across multiple typologies and cities, add life-cycle cost analysis under realistic tariffs, test behavioral sensitivity, and re-run the package under future-climate weather files.

## 6. Study Implications

This study provides calibrated, case-based evidence that a climate-adapted Passive House package can deliver substantial reductions in both cooling demand and whole-building electricity use in hot-arid, cooling-dominated climates. By decomposing the contribution of individual Passive House measures, the results clarify that wall and roof insulation are the primary drivers of savings, while high-performance glazing, external shading, airtightness, and ventilation mainly play supporting roles. This refines the predominantly heating-focused understanding of Passive House performance and supports a more climate-sensitive interpretation of the “fabric-first” approach when the dominant load is cooling rather than heating.

For designers, consultants, and engineers working on detached houses and residential buildings in hot-arid regions, the findings highlight the importance of prioritizing wall and roof insulation as the first step in Passive House design or retrofit. High-performance glazing and fixed external shading can then be applied as complementary measures to temper solar gains on the most exposed façades, while airtightness and ventilation with heat recovery are best specified primarily to stabilize indoor conditions and maintain acceptable IAQ, rather than as the main levers for large cooling-energy reductions. The calibration and scenario-based approach adopted in this study also offers a practical template that design teams can replicate in other hot climates to test Passive House packages and rank envelope options before implementation.

For regulators and decision-makers in hot-climate countries, the demonstrated reductions in whole-building electricity use support strengthening envelope-related requirements in national and local energy codes, particularly with respect to wall and roof U-values and solar-control provisions for residential buildings. The results further suggest that incentive schemes and retrofit programs in hot-arid and hot-humid regions are likely to be most effective when they prioritize envelope upgrades and shading strategies, rather than focusing solely on system efficiency. Finally, the distinction between cooling-only savings reported in many hot-climate studies and the whole-building electricity savings evaluated here is important for accurately estimating the potential contribution of Passive house measures to broader energy-efficiency and decarbonization targets in warm regions.

## 7. Conclusions

This study aimed to apply Passive House principles to reduce energy consumption in a hot-arid residential context, using Riyadh as a representative case for cities in warm regions. The results confirmed that household electricity consumption is heavily concentrated during the summer season, with cooling alone accounting for more than 70% of annual demand. Wall and roof insulation emerged as the most influential intervention, reducing annual electricity consumption by 21% and 15%, respectively. High-performance glazing with a U-value of 1.0 W/m<sup>2</sup>·K and a SHGC of 0.3, combined with fixed external shading achieved an additional reduction of about 3.4%, while improvements in airtightness and the integration of mechanical ventilation with heat recovery showed limited impact under cooling-dominated conditions. When applied as a full package, the Passive House principles reduced the villa’s annual electricity consumption by nearly half (48.1%), confirming the critical role of an envelope-first approach in hot-arid climates. These findings align with regional literature from hot-arid countries, which consistently

identifies the opaque building envelope—particularly roofs and walls exposed to direct solar radiation—as the dominant driver of cooling loads in detached houses. While airtightness and HRV provide large savings in heating-dominated European contexts, their contribution in hot, cooling-led climates is relatively modest, with envelope insulation and solar-gain control delivering the majority of the benefits.

By prioritizing conduction-blocking (low walls and roofs U-values) and solar-control strategies (low-SHGC glazing with shading), Passive House principles can be successfully reinterpreted for hot-arid and other cooling-dominated regions. The results underline that further reductions remain possible through complementary strategies not addressed in this work, such as green roofs, optimized orientation, and self-shading morphologies. In conclusion, while the Passive House standard was originally designed for cold and temperate climates, its core philosophy—minimizing unwanted heat transfer and ensuring controlled, efficient ventilation—remains relevant and effective in hot climates. The Riyadh villa case study illustrates that significant reductions in electricity use are achievable in hot-arid housing, and similar Passive House approaches could support energy-efficiency and sustainability agendas in other warm-climate countries.

**Author Contributions:** Conceptualization, H.A. and A.B.M.; methodology, H.A. and A.F.; software, H.A.; validation, H.A., A.F. and A.B.M.; formal analysis, H.A.; investigation, H.A.; resources, A.B.M.; data curation, H.A.; writing—original draft preparation, H.A.; writing—review and editing, A.F. and A.B.M.; visualization, H.A.; supervision, A.B.M.; project administration, A.B.M.; funding acquisition, A.B.M. All authors have read and agreed to the published version of the manuscript.

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**Data Availability Statement:** The data presented in this study are available on request from the corresponding author.

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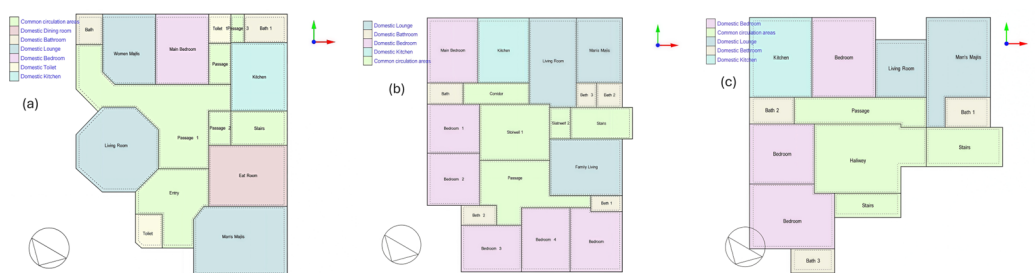
**Conflicts of Interest:** The authors declare no conflicts of interest.

## Abbreviations

The following abbreviations are used in this manuscript:

|      |                                            |
|------|--------------------------------------------|
| ACH  | Air Changes per Hour                       |
| DHW  | Domestic Hot Water                         |
| EER  | Energy Efficiency Ratio                    |
| ERV  | Energy Recovery Ventilation                |
| GCC  | Gulf Cooperation Council                   |
| HRV  | Heat Recovery Ventilation                  |
| HVAC | Heating, Ventilation, and Air Conditioning |
| IAQ  | Indoor Air Quality                         |
| PHI  | Passive House Institute                    |
| SBC  | Saudi Building Code                        |
| SHGC | Solar Heat Gain Coefficient                |
| WWR  | Window-to-Wall Ratio                       |
| XPS  | Extruded Polystyrene                       |

## Appendix A



**Figure A1.** Floor plans used in the simulation model: (a) ground floor, (b) first floor, (c) second floor.

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