Unlocking the Residential Retrofitting Potential in a Three-Degree World: A Holistic Approach to Passive Design in Hot Climates

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Abstract: The Kingdom of Saudi Arabia (KSA), as one of the largest polluters worldwide, has released its Vision 2030 that seeks sustainable development via economic diversification to transition towards lower CO 2 energy systems. Due to fast population and economic growth, the Kingdom is undergoing an increasing volume of construction, which is projected to exacerbate the energy-related emissions. Strategies are needed to decarbonise the housing stock and help bridge the existing performance gap with the updated Saudi Building Code (SBC). This study proposes a holistic retrofitting approach for the Saudi building industry to facilitate the identification of energy consumption reduction optimisation solutions, covering the assessment of insulation, reflective coating surfaces, sun shading devices, efficient glazing solutions, building-integrated renewables, and green roofs. The proposed flexible approach proved how blended retrofit packages provide improved performance, with rooftop photovoltaic microgeneration and improved glazing technologies singlehandedly outperforming the remaining proposals for KSA’s Riyadh climate conditions. Only the photovoltaic system could meet the simulated SBC performance benchmark independently, positioning it as an instrumental tool in improving the overall effectiveness of the retrofit packages.

Keywords: sustainable building development; energy consumption reduction optimisation solutions; holistic retrofitting approach; archetypical building model; building energy benchmarks; passive building design strategies

1. Introduction

The anticipated rise in sea levels and global average temperatures are forecasted to redraw the world map by 2100 [1]. The only solace seems to be meeting the Paris Agreement’s stipulations to slow down these consequences, yet global efforts remain insufficient to meet international goals with multiple indicators pointing towards a dangerous three-degree future, as highly influential countries are hesitant to commit on the favor of national economic interest. Statistics show how cities have transformed into central hubs of man-made CO 2 emissions, as today, buildings consume roughly 40% of primary energy [2]. Accommodating the growing urban population, which could add up to 2.5 billion new inhabitants worldwide by 2050 [3], will manifest into a sharp demand rise for various essential energy resources, especially in the construction and transport sectors. The immense ongoing support for fossil fuel subsidies, among other contradictions in policy responses, has hindered many nations from reaching their ambitious Nationally Determined Contributions (NDCs),

Recently, the World Bank has announced the high vulnerability of the Middle East and North Africa (MENA) region due to its largely unprotected low-lying coasts being prone to an estimated 0.5 m rise in sea levels by 2099 [4]. Its geographical location exposes
it to some of the peak temperatures across the globe, affirming its higher susceptibility to the warming effect. Significant potential for change lies within the Gulf Cooperative Council (GCC) countries, where their heavy reliance on oil and natural gas in external trade and internal services has placed them as some of the 25 highest CO$_2$ emissions per capita worldwide [5]. GCC countries present a strong force against the fulfilment of international goals. This is particularly relevant to the Kingdom of Saudi Arabia, which accounts for 56% of the GCC countries’ CO$_2$ emissions [6]. Its oil-reliant GDP has placed it in a vulnerable spot given the global shifts in the oil markets.

The dramatically increasing volume of construction in KSA represents one of the largest sources of emissions. The expected burgeoning population, recent high economic development, and increased affluence, along with high fossil fuel subsidies, are anticipated to exacerbate energy-related emissions. This fast pace sector growth implies the unsustainable construction of new buildings before the retirement of older ones, especially in the residential sector. Authoritative bodies have stated that the highest number of permits for new construction are licensed for residential projects [7], reflecting their consumption share. Indeed, the bulk of the housing stock has only been built in the past one to two decades [8], which suggests its future influence given a typical building lifetime. Therefore, the decarbonisation of the housing stock presents a highly viable strategy to meet future environmental objectives. KSA has lacked a clear long-term national direction until the release of Vision 2030. It is set to target sustainable development by balancing a mixture of social, economic, and environmental objectives, highlighting economic diversification to non-oil investments.

Achieving sustainable development, by definition, lies in delivering the demand of the present generation without bargaining the future generations’ abilities to accomplish their own by recognising the interlinks between the society, environment, and economy [9]. In the building sector, this translates to creating energy-efficient structures that conserve the consumption of vital local resources for future generations. If Saudi Arabia’s temperature rises as predicted (about 2–2.75 $^\circ$C rise by 2050) [10], adaptability to the climate stresses in building design should be prioritised. Meeting the Saudi society’s needs without breaching the ecological boundaries requires a paradigm shift against inefficient and unsustainable existing practices before causing irreparable harm. The government has recently released its phasing plan in upgrading the Saudi Building Codes (SBC) to elevate the building stock’s performance and drive the needed collaborative contribution from liable stakeholders. The current lack of awareness by industry professionals and the public, besides the low incentives from the government, can be owed to the SBC only becoming mandatory in 2010, three years after being developed in 2007 [11]. There are concerns on whether the measures taken are sufficient to bridge the performance gap between the thermally poor-performing housing infrastructure and the updated binding regulations. After a review of locally conducted research on technical design, policy work, and surveys, many are voicing the need for tailored (place-based) retrofitting programmes to diversify the oil-based economy.

Therefore, this study aims to determine tailored optimised solutions that cater to the case’s climatic conditions and resource availability, covering traditional and novel concepts in local literature. This will be performed via a well-suited computer simulation tool(s) on a validated archetypical building baseline model. It will focus on maximising the energy efficiency of the problematic building envelope elements by exploiting selective passive design principles, unveiling a suitable holistic approach for Saudi designers that enables the accurate identification of suitable candidates for a tailored retrofit programme thus, addressing the following research questions:

1. Can significant energy savings be achieved with traditional retrofit techniques? Is there a need for the introduction of more novel alternatives?
2. Which of the packages are more successful in the current conditions?

Objectives and Paper Structure

Based on the background provided, the objectives to be delivered are:
(1) Translating the SBC requirements into an ideal building model and/or a performance benchmark for a comparative assessment of the selected baseline model and the optimised scenarios.

(2) Test a range of retrofit strategies addressing key performance requirements and energy savings measures against SBC benchmarks.

(3) Formulate further optimisation arrangements based on potential alternatives that combine the favoured tested individual strategies.

The remaining of the paper would be structured as follows: Section 2 provides a comprehensive review over the case study and relevant literature available for the traditional and novel retrofit strategies. Section 3 shows the formulated methodology and additional information for simulation. Section 4 presents the key findings and discussions. Conclusions are then drawn in Section 5.

2. Background Review

2.1. Case Study Country Profile: Kingdom of Saudi Arabia

Tables 1 and 2 provide the relevant fundamental information about the case study, including the climate description.

Table 1. Fundamental information about the case study country [12,13].

| Country        | Saudi Arabia                      |
|----------------|-----------------------------------|
| Geographical footprint | Approximate coordinates of 16–32° N, 34–55° E, Approximate area 2,252,500 km² |
| Natural resources [12] | **Hydrocarbons:** Ranks 5th in proven reserves of oil and natural gas globally at a combined estimate of 204.5 trillion cubic feet (2016) **Renewables:** High solar resource (3245 daylight hours of solar radiation at over 2200 kWh/m²) and attractive wind resource in the Eastern provinces (e.g., a mean annual wind speed of 6.7 m/s at 50 m above ground in Yanbu) |
| Case study city | Riyadh City                      |
| Location       | Coordinates: 24.714° N, 46.675° E |

Table 2. Climate description and zonal breakdown of Saudi Arabia [8,14].

| Overview                                                                 |
|---------------------------------------------------------------------------|
| **Semi-to Hyper Arid, with Exceptionally Low Rainfall and High Evapotranspiration** |
| Zone 1 Subtropical, Mediterranean subzone, mountainous subtype            |
| Zone 2 Hot and dry with a maritime desert subzone                         |
| Zone 3 Hot and dry with maritime subzone                                  |
| Zone 4 Cold and dry with a desert subzone                                 |
| Zone 5 Hot and dry with a desert subzone                                  |
| Zone 6 Al-Rub Al-Khali is not inhabited and has no weather data           |

2.2. The Current and Future Role of the Built Environment Sector

Having clarified the importance of improving the domestic energy economy to support growth, especially via non-oil means, McKinsey Global Institute (MGI) research [14] has verified that construction is among the proposed eight non-oil sectors that can drive growth in the future [15]. The local construction sector is already a top leader in the Middle East and is considered one of the fastest-growing marketplaces worldwide. It is set to more than double, from $45.33 billion in 2016, to hit a record high of $96.52 billion by 2025 [16]. Though highly attractive for investment opportunities, it raises concerns about the country’s capability to handle the consequent rise in energy demand and the
ecological impact of this rapid growth. Over the last decade, the building sector (residential, commercial, and governmental buildings) has been steadily consuming around 80% of the country’s total electricity consumption [7]. A study by Krarti [8] has highlighted the considerable untapped potential for energy savings via energy efficiency improvement of both new construction and retrofitting of the existing buildings’ energy systems. According to the Saudi Energy Efficiency Centre (SEE, the entity responsible for performing energy audits, load management, regulation, and education [9]), a few challenges have hindered the progress so far, such as [12]:

- The high portion of non-thermally insulated housing stock (nearly 70%).
- The low electricity bill (<100 SR/month for 65% of consumers) disincentivises conscious consumption.
- Lack of public awareness led to a low general tendency to purchase high-efficiency devices and/or the replacement of existing less efficient devices.
- There is a weak supervision protocol for the assessment and maintenance of these products.

Given KSA’s energy consumption projections, building energy efficiency has recently become at the forefront of KSA’s energy policy objectives, focusing on building performance regulations and energy price reforms. As mentioned before, the government has gradually introduced its own set of building standards and regulations (the SBC). Most studies in literature focus on the highlighting the potential effect that the SBC can have on the overall energy efficiency of the Saudi stock with little effort to gauge the true impact that it had since its release ten years ago. Though quantifying its effect on energy demand alone might be challenging as it was accompanied by other incentives listed below. This brings an opportunity for further research in this area. Moreover, uneconomical consumption has already been indirectly encouraged through KSA’s low energy prices, where during the boom decade alone, the energy consumption has almost doubled. This changed in 2017 when the government introduced plans to reduce subsidies to gasoline, natural gas, and diesel with a target of meeting international prices by 2025 [17].

Nevertheless, the identified large share of aging infrastructure will present a significant retrofitting challenge in the future, given the correlated expensive price tag. Retrofit costs differ subject to building age, location, and type. Large investments are being pumped into the retrofit of villas and apartments of the Middle and Western regions (i.e., Riyadh and Jeddah), where the largest Saudi population resides, and the vast majority of the housing stock’s electricity consumption is concentrated [8].

Figure 1 summarizes a comparative breakdown of the housing type’s influence. An average energy use intensity (EUI) value of 149.6 kWh/m²/year was noted across the housing stock [8] where air-conditioning represents more than 70% of the total stock’s electricity consumption [12]. This is reflected in the typical household expenditure breakdown, which is dominated by energy bills [18].

![Figure 1. Breakdown of KSA's housing stock based on type [8].](image-url)
2.3. Engineering Design Solutions

The case assessment of KSA revealed the opportunistic, largely untapped energy savings potential in the existing building stock. If harnessed effectively, this could facilitate achieving the national development goals. This section will review the relevant residential retrofitting strategies based on the following:

2.3.1. Region of Study

The highest population rates and consumption levels are concentrated in the middle region (i.e., Riyadh, climate zone 5) [15].

2.3.2. Type of Housing Stock

Villas account for the highest energy consumption share. A survey revealed that they make up 40% of the residential stock, implying they are a strong housing preference for the typical Saudi household [19].

2.3.3. Age of Model

Given that the bulk of the housing stock was built in the past 10–20 years [8], an archetypical baseline model from this period (see Section 3) will be specified for the simulation stage.

2.3.4. Design Target

Energy-use analysis reviews have revealed that air conditioning loads often surpass 65% of the annual electricity consumption of non-insulated villas in Riyadh [7], noting that almost 70% of the stock is non-thermally insulated. Therefore, minimising the space cooling demand and heat gains will likely be the focus of any strategy.

2.3.5. SBC Regulations

Riyadh falls in Zone 1, where its equivalent minimal performance requirements, including U-values and Solar Heat Gain Coefficient (SHGC; it quantifies the absorbed solar heat gain proportion through glazing) for the building envelope elements (i.e., walls, floor, roof, fenestration), are listed in Appendix A.

2.3.6. Local Research: Passive Design Strategies and Precedents

Passive design (this comprises of all strategies targeting the improvement of building energy management without external mechanical aids, including the microclimate [14]), renewable energy, and building performance analysis were selected as the core design approaches for this study. This stems from the substantial familiarity with these concepts among the local academia and the industry, as reflected by multiple surveys [9,20]. This stresses the role of the building envelope’s multi-functional adaptability beyond the structural and/or architectural purposes since it also acts as a protective barrier against the harsh climate conditions [19]. Between 40–45% of the total thermal load of a building is owed to the building envelope (subject to the glazing area and infiltration rates) [12]. The weatherisation of building shells has been discussed by various studies, which tested the individual contribution of these elements and implemented energy efficiency measures. These have covered insulation, glazing properties, thermal mass, shading devices, landscaping alternatives, and renewable energy technologies [7,19], as summarized below.

2.3.7. Wall and Floor Systems

Most investigations for the energy efficiency improvement of walls have trialled the optimisation of insulation techniques, including different types, arrangements, and thicknesses. A design procedure has been proposed by AbdelRahman and Ahmed [21] for the selection of insulation type and thickness, examining the optimum placement of polyurethane and polystyrene boards for clay bricks and hollow concrete block walls (traditional building materials) via a lifecycle cost analysis. The results revealed that the
exterior wall side, for places with high diurnal (where diurnal refers to a considerable temperature differential between day and night) surface temperatures, is favoured to minimise thermal strains. Similarly, Saleh [22] advised positioning 5–10 cm thick boards externally. Al-Sanea [23] has manipulated three wall-insulation configurations in a Riyadh-based case study. The optimisation findings, which focused on energy savings and the present value method, demonstrated that multiple layers of insulation outperformed a single layer (without varying the total thickness/thermal mass), resulting in a 20% peak cooling load reduction and a 6 to 12 h increase in lag time. Other low-cost changes suggest using reflective paints due to their lower solar radiation absorptance properties [24], yet in KSA’s dusty environment, regular maintenance of the radiation barrier must be factored. Flooring systems were investigated at a lesser rate in the literature. The views from a Delphi-based survey [20] (which collected views from a diverse mixture of participants, including decision-makers/policymakers, academia professionals, and building professionals) have suggested using finishing materials with high R-values and a strong preference for the use of mud insulation, mortar, concrete tiles, layers of sand, or natural stone.

2.3.8. Roof Systems

Saudi houses are usually characterised by flat roofs, which are not thermally ideal, especially when exposed to vertical direct solar radiation for most sunshine hours of the day. Suehrchke et al. [25] estimated that the roof surface can absorb from 20–95% of the solar radiation, particularly under clear sky conditions. As cited by Alaidroos [19], Al-Sanea’s findings [26] agree, recording a solar radiation share of more than double that of heat convection and conduction. The simulation-based study compared the influence of different insulation materials with a 5 cm thickness on the daily average heat transfer load of six typical roof structures in KSA, where the base-case model was an uninsulated heavyweight concrete roof. The results noted a drop of 22–45% of the reference energy use level with an improved thermal performance when the insulation layer is placed closer to the roof’s interior surface. More advanced passive cooling techniques were investigated, including the cool roof concept, which was estimated to decrease the cooling load by up to 40% (subject to variance in the spraying period, the mass of sprayed water, uniform versus time-dependent spraying, etc.) in hot, dry conditions [27,28]. Besides, the lower and more stabilized roof surface temperature, which can reduce mechanical stress and maintenance hence extend its lifetime [29].

The main surface properties that affect the roof temperature are albedo and emissivity. The former can vary between 0.1 (very black) and 0.8 (very white), where the lighter end is more useful for flat models as it can reflect up to 80% of insolation [28]. Akbari [30] showed how increasing the albedo by 0.2–0.6% in hot climates can lower the cooling load by 20%. Al-Hemiddi [28] has tested the concept’s applicability in Riyadh, investigating a roof with soil shaded by 10 cm of pebbles, achieving an average internal temperature reduction of 5 °C in August. Hosseini [31] has stated that these models are optimal for locations with low or no heating load, especially as they tend to increase the heating load. Becherini et al. [29] also recommended them for hot climates where no winter heating penalties have to be considered, analysing a second generation of non-white coatings with an albedo (0.8+) higher than the traditional counterparts. Levinson [32] recommended regular maintenance to the cool roof surfaces that could naturally deteriorate with age and dust. The industry’s experts have highly rated insulating concrete roof structures and exploring green roofs [20]. The latter is a rather novel research area locally, with only a few studies investigating its integration as part of a holistic retrofit strategy. Its evapotranspiration properties also add to its cooling benefits. Alexandri [33] showed how similar models have lowered surface temperatures by 12.8 °C in Riyadh. They can also be combined with a ‘flying’ roof, a fixed/retractable structure to protect from direct insolation.
2.3.9. Fenestration and Shading Systems

The literature has strongly advocated double-glazing systems over the typical clear single pane, stating the strong influence of using reflective silver low-E glass [12,34]. Alaidroos [19] verified the recommendation, favouring argon-filled over air cavities for their lower SHGC and U-values. Kari [7] has labelled this system type as a costly instalment relative to other passive strategies, though it is still more affordable than the more efficient yet not as cost-effective triple glazing assembly [35]. Alternatively, shading is one of the most popular and important principles in literature for slashing solar gains in hot climates [35], which can come as internal or external instalments. Though Aldossary [35] argued that external arrangements are more effective since internal devices can absorb and radiate heat gains into the conditioned space, highlighting that window-to-wall ratio (WWR) can be a determining factor for cost-effectiveness. Alaidroos agreed by stating that overhang design is more effective for larger windows by showing how a 1 m projection has only resulted in a maximum annual reduction of 6.3% for a villa with 13% WWR. The Saudi industry’s views endorse shading strategies as viable climate-responsive solutions, highly rating the use of [20]:

- Canopies on top of windows (e.g., overhangs, fins, egg-crates, louvres).
- Planting shades instead of steel shades.
- Sun reflective design techniques.
- Increasing glazing thickness (with air/argon-filled cavity).
- Highly air-tight windows.

2.3.10. Landscaping Design

Landscaping has been found to contribute to a considerable solar gain reduction. Omer [36] suggested using its features as a means of thermal control. The directly overhead sun’s position on typically hard reflective surfaces surrounding the houses can increase indirect heat gains. Al-Naimi stated that integrating green features (e.g., trees, shrubs, grass) can aid in diffusing the reflected solar radiation and providing shade, besides creating a cool microclimate, and reducing dust. Bajwa [37] has compiled the factors to consider for the design of an energy conservation landscape (e.g., plant species, foliage density, water and soil requirement, ease of maintenance), including their placement and effect on air temperature, humidity, radiation, and air movement. There is a consensus by the industry professionals over effective courtyard landscaping to provide shade, estimating an average of three trees per property can reduce the annual and peak cooling load by up to 7.1% and 2.3%, respectively [20].

2.3.11. Additional Features and Considerations

Riyadh is exposed to vertical solar insolation under clear sky conditions, as it lies within the so-called “sunbelt” (40° N ≤ Latitude ≤ 40° S) that extends across the length of Saudi Arabia (31° N ≤ Latitude ≤ 17.5° N) [6]. The high solar resource depicts the attractiveness of photovoltaics (PV—a technology that captures solar energy and transforms it into electricity at point-of-use) and building-integrated photovoltaics (BIPV) deployment (BIPV refers to the replacement of conventional building envelope materials by the integration of PV cells with various applications (e.g., walls, windows, shading devices)), maximising buildings’ adaptability to climate change. Coupling clean energy microgeneration with efficient building fabrics is also Saudi industry-approved [20,38]. Yet, their local implementation is still rare given that until the recent 2020 release of the green building code, the country lacked any demand-side clean energy integration mandates. As for solar thermal applications for domestic hot water (DHW) heating, some researchers advise against it, favouring PV due to lower retrofitting costs associated with not needing the replacement of any existing systems, unlike the former [35]. Besides, the widely adopted DHW systems in KSA comprise of bathroom/kitchen dedicated boilers that use electricity too. Thus, the PV-generated electricity would slash both the air-conditioning and DHW system energy demand. A rough rule-of-thumb was proposed that 15% of electricity can be captured from
solar radiation, assuming it occupies 30% of roof area [35]. Finally, it should be noted that literature has also examined various other passive design alternatives that were rejected for this study, as they do not apply to pre-existing buildings (out of scope). These include the influence of orientation, WWR, window orientation, building construction type, shape, size, and room distribution [20], and other irreversible design decisions.

3. Research Methodology

3.1. Identification of Selected Methodology Frameworks

This study’s nature and its set objectives impose requirements and restrictions that need to be evaluated for the identification of the appropriate testing framework. Certain factors were raised by researchers [39] aided in favouring computer simulation over other methods, including the project stage and the easier adaptability of test parameters. Given that buildings within themselves are systems that comprise smaller sub-systems that interact dynamically, a modification in one part can influence its whole operation. This is the challenge behind retrofitting; the modifications need to consider the existing constraints from a previous designer’s decisions. Therefore, the general framework of the systems approach, though usually used for new build design [40], can work in principle as a base for retrofit design optimization. The framework illustrated in Figure 2 can aid in deriving not only the optimal solution but a series of other alternatives that offer flexibility for decision-makers and designers. The selected simulation tool, Integrated Environmental Solutions-Virtual Environment (or IES-VE), was favoured for its industrial established reputation as an integrated energy analysis platform among academics [41], architects, and engineers for the design and retrofit of buildings, known to convert complex thermal calculations into easy-to-interpret technical data and visualization [42].

Figure 2. The retrofit approach-tailored energy modelling methodology flowchart.

3.2. Energy Modelling: Formulation of Test Scenarios

3.2.1. Energy Modelling: Identifying Restrictions

One of the objectives is to define a replicable design approach, as delivered in this chapter. As for site specifications (constraints), Riyadh’s building stock was reviewed by many researchers as cited by Aldossary [19] who identified an archetypical building model for its villas, specified in Figure 3, Tables 3 and 4. The significance in selecting a representative model lies in developing a wider view of the common design issues in the existing stock. As shown in Table 5, all elements failed to achieve the SBC requirements by surpassing the minimal requirements except for the floor and door.
Table 3. The selected baseline building parameters.

| Floor Dimensions (L × W) | Number of Floors | Building Height | Gross Floor Area | Gross Wall Area | Window-to-Wall Ratio (WWR) | Building Capacity | Operations Parameters |
|--------------------------|------------------|-----------------|------------------|-----------------|---------------------------|-------------------|----------------------|
| 15 m × 17.5 m            | 2                | 7 m             | 525 m²           | 455 m²          | 13%                       | 6 occupants       | Check Figure 4       |

Figure 3. The selected archetypical baseline building model and its orientation.

Table 4. Operational parameters of the case study.

| Lighting Power | Equipment Power | Domestic Hot Water Requirement | Temperature Setpoint | HVAC System  | Energy Efficiency Ratio (EER) | Typical Operation of Conditioning Plants |
|----------------|-----------------|-------------------------------|----------------------|--------------|------------------------------|------------------------------------------|
| 4 W/m² (~600 L/12) | 3.5 W/m²         | 11.4 L/person/day             | 22 °C (heating), 25 °C (cooling) | Split DX     | 7.5 (low)                    | 24 h/day                                |

Figure 4. Operational schedules of the selected case.
Table 5. Thermal specifications of the selected archetypical baseline building (the u-values were estimated using IES-VE).

| Element & Composition                                      | Actual Thermal Performance | SBC Thermal Performance |
|------------------------------------------------------------|----------------------------|-------------------------|
| Walls (20 mm plaster-150 mm hollow concrete block-20 mm plaster) | U-value: 0.5450 W/m²K     | U-value: 0.340 W/m²K    |
| Roof (10 mm built-up roofing-200 mm concrete roof slab-13 mm plaster) | U-value: 0.5821 W/m²K     | U-value: 0.202 W/m²K    |
| Glazing (clear single pane, wooden frame)                  | U-value: 3.8701 W/m²K     | U-value: 2.670 W/m²K    |
| SHGC: 0.5470                                               | SHGC: 0.25                |
| Floor (ceramic tiles-100 mm concrete slab on grade)        | U-value: 0.6085 W/m²K     | U-value: 0.900 W/m²K    |
| Door (oakwood)                                             | U-value: 1.3783 W/m²K     | U-value: 2.840 W/m²K    |

3.2.2. Energy Modelling: Defining Input Parameters

The design know-how is an essential factor for ensuring that the finalised retrofitting packages are based on informed decisions. Another criterion includes the typical operational loads/schedules, which, like the building model, were determined from the literature [8], as shown in Figure 4. As for the design climate conditions, IES-VE provides pre-set weather files for the main cities worldwide. However, the nearest available site for Saudi Arabia is in Jeddah (a different climate zone). In this case, an external source for Riyadh weather data was imported from Energy Plus in a compatible (.epw) file format, which was also verified against the reliable Meteoblue and NASA databases [43,44]. The city’s high-temperature range indicates a corresponding high cooling load, especially in the summer, when it peaks alongside the highest insolation levels and driest periods (clear skies). The recommended internal comfort conditions for Riyadh were verified using the ASHRAE-sourced Psychrometric chart [45]. The chart suggests that the ambient conditions fall within the comfortable range for only 7% of the year (601 hours). This depicts the challenge in incorporating suitable passive design strategies that can fit the harshness of the external environment.

3.2.3. Energy Modelling: Design Procedures and Performance Indicators

After identifying the baseline case and computing its parameters into IES-VE for performance assessment, a load analysis was completed using Apachesim tool in IES-VE to determine the largest contributor to the building’s annual energy consumption (See Section 4). The goal was to identify the least efficient envelope elements that propagate the highest share of heat. From Section 2.3.7 to Section 2.3.11, the most (theoretically) effective proposals were selected (around 2–4 strategies for each building envelope element), varying from low-cost, simple, and traditional to high-end, advanced, and locally novel alternatives (See Table 6). These were first tested individually to quantify their separate energy-saving potential. Some of the more advanced strategies, marked by (*), required additional modelling considerations. Then, nine unique combinations were generated from the five best strategies of each element group (three per package). Then, the best performing combos will be assessed to rank the favoured retrofitting packages, as shown in Figure 5.
Table 6. Selected strategies for simulation testing.

| CODE | VARIANTS                        | SPECIFICATIONS                                                                 | JUSTIFICATION                                                                 |
|------|---------------------------------|-------------------------------------------------------------------------------|-------------------------------------------------------------------------------|
| W1   | External insulation             | Add a 100 mm-thick polyurethane board to all the exterior sides of the walls. | These variants are investigating whether the cool wall model and higher building envelope airtightness can reduce or eliminate the reliance on wall insulation. |
| W2   | Internal insulation + reflective coating | Add a 50 mm-thick insulation board to all the interior sides of walls and paint a coating with an albedo of 0.6 (from an assumed 0.4 for baseline). |                                                               |
| W3   | Airtight envelope + reflective coating | Impact of lowering infiltration down to 0.5 ach and a reflective coating of 0.6. |                                                               |
| R1   | Reflective roof                 | A roof coating with an albedo of 0.6.                                         | The presented roof strategies were selected as they were reported less frequently, especially in local literature. |
| R2 * | Flying roof                     | Placing a 40 mm thin concrete shading south-facing platform at a 15° tilt to cover 50% of the flat roof area. |                                                               |
| R3 * | Green roof                      | See Section 3.2.6 for specifications.                                         |                                                               |
| R4   | Shaded roof                     | Measures the shading effect of rooftop PV integration (M1) on solar gains.     |                                                               |
| F1   | Double-glazing system           | Increasing the glazing thickness by using two panes with reflective low-E surfaces and an argon-filled cavity. | Comparing the individual potential of reflective surfaces, glazing thickness, and external shading devices to derive the case’s optimum solution. |
| F2   | Triple-glazing                  | Uses three clear panes and an air cavity.                                    |                                                               |
| F3 * | F1 + Overhang                   | Test 1 m overhang projections with the double-glazing system from F1.         |                                                               |
| L1 * | Green courtyard                 | Change surrounding surfaces from hard concrete to a green surface.            | These were proposed to investigate the influence of surface materials properties on cooling load reduction. |
| L2 * | Green shading                   | Cover F3 with a green surface.                                               |                                                               |
| M1 * | Rooftop PV system               | PV south-facing array that covers 15–45% of the accessible roof surface area. | The balance between its roof shading impact and generation potential was studied. |
| M2 * | PV shading device               | F3 + PV panels integrated on top of the shading device’s surface (tilted and flat). | Very few reports were found on the potential of other PV solutions besides rooftop systems in local literature. |
| M3 * | PV windows                      | Semi-transparent PV cells integrated as part of the south-facing windows.     |                                                               |

* These strategies require additional modelling considerations and were discussed further in the following sections.
3.2.4. Shading Design Strategies

A solar analysis was performed on the baseline building’s fenestration using SunCast and Apachesim in IES-VE. Results revealed that the South-facing glazing had the highest peak incident solar flux followed by the West and East-facing sides but at varying seasons. The design opted for a fixed alternative with little user intervention (i.e., overhangs and fins), where the former is generally recommended for South-facing windows and the latter for East and West-facing glazing. Their sizing was based on peak conditions (highest incident solar irradiance), which varied from one façade to another. The case specifications and shading design targets were defined in Table 7. The design method relies on utilising solar geometry principles and Riyadh’s stereographic (Sunpath) diagram [46] that has the location’s solar azimuth ($\gamma_s$) and altitude ($\alpha$) of a typical year.

**Table 7.** Window specifications and shading design targets.

| Window Type | 1 | 2 | 3 |
|-------------|---|---|---|
| Dimensions  | 2.75 m × 1.25 m | 1.25 m × 1.25 m | 0.75 m × 1.25 m |
| Orientation | West (270°)/East (90°)/South (180°) | South (180°) | East (90°)/West (180°) |
| Target shading period (peak conditions) | West: Equinox (21 Mar/Sep), afternoon | East: Equinox (21 Mar/Sep), morning | South: Summer solstice (21 Jun), midday |

The horizontal (HSA) and vertical (VSA) shadow angles, shown in Figure 6, can be identified based on the target shading period to derive the required depth of the vertical fins ($D_v$) and overhangs ($D_o$) relative to the window’s orientation ($\gamma$) and size, using Equations (1) and (2) [47].

$$D_v = \frac{W}{\text{Tan}(\text{HSA})}$$  \hspace{1cm} (1)

$$D_o = \frac{L}{\text{Tan}(\text{VSA})}$$  \hspace{1cm} (2)

where ($W$) and ($L$) are width and the length of the casted shading.
This is to avoid large extrusions and the associated load bearings. The calculations provided once the room is defined. A simple way to assess this, is by using the average angle in degrees measured relative to the centre of the window (\( \alpha \)).

Design parameters can allow a sufficient and visually comfortable amount of daylight for the fenestration design parameters can allow a sufficient and visually comfortable amount of daylight for the daylight factor (\( DF \)).

Figure 6. Shading Design Parameters.

Window types 1 and 2 on the target façades were favoured for shading. Window type 3 was disregarded due to its small area, assuming it can support daylighting with the North façade (note: internal design conditions are out of scope). The HSA and VSAs were set so they could cast a shade length/width of a minimum of 60% of the window dimensions. This is to avoid large extrusions and the associated load bearings. The calculations provided the minimum dimensions, which were rounded up to 1 m after simulations. No influence was recorded for vertical fins, so they were later removed. The 1 m overhangs were placed only on the South façade as the other façade’s influence was minimal. Figure 7 displays the final arrangement.

Figure 7. Shading devices arrangement.

As for the flying roof model specified in Table 6, IES-VE does not allow the addition of slanted structures (to the extent of the authors’ knowledge). Instead, a pitched roof was modelled with openings (holes) to allow for airflow and diffused solar radiation for more accurate simulation results.

3.2.5. Fenestration Design Optimisation: Heat Gain Reduction Versus Daylight

The fenestration design parameters such as the glazing specifications (i.e., reflectance (\( R \)), transmittance (\( \tau_\alpha \)), and the exposed window area (\( A_e \)) can be modelled and/or computed into the simulation software directly to assess their impact on heat gain reduction. As for its influence on daylight, this also partly relies on room geometry, and can be predicted once the room is defined. A simple way to assess this, is by using the average daylighting factor (\( DF_{AVG} \)). It is useful in verifying whether the varying fenestration design parameters can allow a sufficient and visually comfortable amount of daylight for the occupants, without compromising additional lighting. The daylighting factor is given by Equation (3) [48], and it relates to the window properties indicated above and the total floor area (\( A_f \)), plus the impact of any surrounding external obstructions via their sky angle in degrees measured relative to the centre of the window (\( \theta \)):

\[
DF_{AVG} = 0.3 \left[ \frac{\tau_\alpha A_e \theta}{A_f (1 - R^2)} \right] \%
\]

For residential applications, the average daylighting factor should ideally fall between 1.5% and 2% [49]. Table 8 displays the set design parameters for the three tested fenestration strategies. Other assumptions made include.
Table 8. The set fenestration design parameters for F1, F2, and F3.

|       | F1       | F2       | F3       |
|-------|----------|----------|----------|
| $\tau_w$ | 0.34     | 0.34     | 0.78     | 0.78     | 0.34     | 0.34     |
| $A_g$ ($m^2$) | 41.88   | 29.38   | 41.88   | 29.38   | 41.88   | 29.38   |
| $\theta$ | 90°      | 90°      | 90°      | 90°      | 51.34°  | 51.34°  |
| $R$ | 0.32     | 0.32     | 0.07     | 0.07     | 0.32     | 0.32     |

- Reflectance and transmittance values are extracted from IES-VE packages.
- No surrounding obstructions for ground floor ($Gf$) windows and the overhangs were considered for first floor ($f1$) windows.
- Only 75% of each floor (see Table 3) is accounted for, and also, assuming that half of the gross floor area is subjected daylighting in each direction.

3.2.6. Green Design and Modelling

The literature suggests that landscaping can generate a healthy share of energy reductions if integrated as part of a holistic retrofit. There is currently an encouraging trend in the city of Riyadh towards increasing plantation [50] using native plant species that require little to no irrigation. The study will focus on the incorporation of three alternatives: green courtyards, roofs, and overhangs. For all three strategies, the selected type of plant is key for effective and sustainable performance. The goal is to utilise species that would require the least human intervention and maintenance. Other factors include the base-case building performance, feasibility, and application type. The spatial limitations of some courtyards might restrict the application of green courtyards. Saudis can build up to a maximum of 60% of their land plots [35]. It is usually utilized fully, as occupants tend to favour larger living spaces. This leaves a limited area for plantation. Riyadh’s wind rose implies that the North-Western direction is favoured, although, in other cases, obstructions and surrounding site conditions might indicate otherwise. Green roofs are more complex and expensive as an initial investment and maintenance, but their benefits and the correlated avoided energy costs can potentially increase their viability. They comprise a composite structure that can come in a prefabricated, commercial, and modular form. There are two main types of green roof: extensive (lightweight, low maintenance) and intensive (heavy-weight, high maintenance). Given the application size, type, and load-bearing considerations, besides its low-hassle care, the extensive roof was favoured. Literature proposals have guided the selection of the design parameters shown in Table 9; as recommended in Asif and Khabaz [51,52] who have tested green roof models on a similar roof structure to that of the base-case (solid concrete structure with no air spaces).

Table 9. Tested green roof specifications [51,52]:

| Element                  | Technical Specifications                                                                 |
|--------------------------|-------------------------------------------------------------------------------------------|
| Vegetation cover         | Shrubs at 0.1 m high; Surface solar absorptance of 0.7; Green colour reflectivity of 0.29; Has an R-value of 1.610 m²K/W |
| Growing medium           | A 200 mm thick layer; Has moisture content of 40% and thermal conductivity of 1.580 W/m K; A minimum 3 inch (76.2 mm) layer to avoid root damage; Vegetation and the soil layer were modelled as a one |
| Filter                   | Assumed to be 30 mm thin; Often plastic and modular                                        |
| Insulation (Variant R3(a)) | A 50 mm polystyrene layer; Conflicting views were found regarding its necessity. Supporting argument states that it acts as an additional protective barrier against condensation and physical damage |
| Waterproofing            | 10 mm thin; Thermal conductivity of 0.033 W/m-K                                            |
| Roof deck                | The existing roof specification were kept constant                                         |
3.2.7. Photovoltaic Solutions

Designing effective PV solutions requires a comprehensive understanding of the solar resource, geographical location, climatic conditions, and site conditions with respect to the design objectives. Given that the Saudi government has recently initiated the application of a net metering scheme for small-scale grid-connected PV systems for the entitled customers, the study selected this connection arrangement for all three strategies (M1, M2, M3). It also has not been widely reported in local literature, especially the latter two. The main design parameters, include the optimum tilt angle, suitable module specifications (e.g., cell type, efficiency, cell temperature coefficient (which measures the variation in cell temperature to changes in ambient temperature and should be kept at a minimum)), and array size, besides other supplementary components (e.g., inverters). The goal is to measure their potential output and any other secondary energy savings on the building envelope (e.g., roof shading effect (R4)). A general rule-of-thumb for Northern hemisphere locations recommends orientating the panels Southwards with a tilt equivalent to the geographical latitude.

In Riyadh’s case, this suggests that a tilt angle of ~25° is favoured. Module selection was based on commercially available products, besides other constraints such as the building elements’ sizes (e.g., accessible roof area, window size for PV shading purposes). For the rooftop PV system (M1), it was sized to cover 15–45% of the accessible roof space (in 15% increments), assuming 40% is denoted for the HVAC plant (and related components) and to allow roof access for maintenance work. The design also considered spaces in between panels to prevent array self-shading losses. The selected module specifications are summarised in Table 10 (see Appendix B for array sizes) with a compatible inverter (the inverter power was set to vary with the PV size, with an inverter minimum rating of 75% of the PV system capacity will have no power loss risk and to avoid oversizing.) (see Table 11).

Table 10. PV module specifications [53].

| Parameter               | Criteria                  | Selection                                      |
|-------------------------|---------------------------|------------------------------------------------|
| Model                   | –                         | G Solar (GSM310)                               |
| Size                    | –                         | 0.992 m x 1.640 m                              |
| Cell technology         | Maximum power output (module efficiency, $\eta$) | Mono-Si: $P_{\text{max}} = 310 \text{ W}_p$; $\eta = 19.05\%$, (@STC *) |
| Electrical parameters   | IV performance            | $V_{\text{mpp}} = 33.25 \text{ V}$, $I_{\text{mpp}} = 9.33 \text{ A}$ |
|                         |                           | $V_{\text{DC}} = 40.63 \text{ V}$, $I_{\text{SC}} = 9.85 \text{ A}^{**}$ |
| Operating environment   | Efficiency temperature coefficient ($\beta_c$) | $\beta_c = -0.393$ (@NOCT ***) |
| Reputation & warranty   | Long 25-year life and low power degradation rate | Manufactured and designed by G solar. |

* standard testing conditions (irradiance 1000 W/m², Air mass 1.5, cell temperature 25 °C). ** $V_{\text{mpp}}$: voltage maximum power point, $V_{\text{DC}}$: open circuit voltage, $I_{\text{mpp}}$: current at the maximum power point, $I_{\text{SC}}$: short circuit current. *** nominal operating cell temperature (45 °C, irradiance 800 W/m², air temperature 20 °C, wind speed 1 m/s).

Table 11. Inverter specifications [54].

| Parameter               | Inverter Model            | Inverter Efficiency | Warranty | Maximum Input Current ($I_{\text{DC}}$) | Operating Voltage ($V_{\text{DC}}$) |
|-------------------------|---------------------------|---------------------|----------|-----------------------------------------|-------------------------------------|
| Description             | Single-phase Eversol TL2000 | 97%                 | 15 years | 11 A                                    | 90–450 V                            |
The same products were used for M2, where one module was placed on f1 overhangs. Due to modelling restrictions, the PV panel will be tilted on a longer flat overhang ($D_0 = 1.77$ m) to mimic the tilt shading effect (see Figure 8).

![Figure 8. Arrangement of PV-integrated shading devices.](image)

PV windows are a rather novel concept in building applications, especially in KSA. Its design generally aims to strike a balance between system efficiency, solar gains, and daylighting. They were derived from successful precedents in similar climate conditions that have examined the power output of semi- and fully transparent crystalline and amorphous BIPV technology on double-glazing systems [55,56]. For a fair comparison between the PV solutions, the same cell type technology was favoured (i.e., crystalline technology). A semi-transparent PV window (STPV) system was designed by a Chinese manufacturer (see Table 12), noting that the PV market in KSA is heavily reliant on imports from China, so, even if not currently available commercially, there is an opportunity for the promotion of this module type in the future if deemed cost-effective.

| Layer          | STPV layer | Air gap | Clear pane |
|----------------|------------|---------|------------|
| Thickness      | 4 mm       | 9 mm    | 5 mm       |
| Solar transmittance at normal incidence | 0.224 | – | 0.811 |
| Visible transmittance at normal incidence | 0.225 | – | 0.887 |
| Thermal conductivity | 0.0415 | – | 0.0133 |

**Table 12. PV window specifications [56].**

| Parameter                  | Value   |
|----------------------------|---------|
| $\eta$                     | 13%     |
| $I_{SC}$                   | 6.986 A |
| $V_{OC}$                   | 85.6 V  |
| $I_{mpp}$                  | 6.221 A |
| $V_{mpp}$                  | 68.3 V  |

3.2.8. Energy Modelling: Performance Benchmarking

Validation procedures and benchmarks were used to ensure higher reliability of the results. The average EUI value for the selected Riyadh villa model quoted from literature (228 kWh/m²) was used to verify the simulation results of the baseline model. As for setting a representative performance target of the SBC requirements, the government has proposed different assessment procedures for design proposals rather than building performance benchmarks and/or rating tools. The study is concerned with the influence of the retrofit design strategies on overall building performance, specifically the cooling load. Therefore, the selected assessment method involved generating a benchmark by computing the minimal SBC U-value and SHGC requirements into the baseline model and calculating
the corresponding annual cooling (and dehumidification) load as it makes up the total annual energy consumption (see Section 4.1). An aggregated value can also be derived by using the gross floor surface area of the building using (Equation (4)), which can be used as a performance benchmark. When compared to ASHRAE’s code for energy efficiency improvements for Riyadh’s climate zone (0B: Extremely Hot and Dry), the SBC-estimated benchmark of 197.94 kWh/m$^2$/year fell short to meet ASHRAE’s 100 kWh/m$^2$/year target [57]:

$$q_{SBC} = \frac{Q_{\text{annual}}}{GSA_{\text{floor}}} \tag{4}$$

4. Key Findings and Discussions

4.1. Baseline Model Assessment

After modelling the baseline building on IES-VE using its ModelIT feature, a load analysis was performed on Apachesim. The results extracted from Vistapro confirmed that the highest load type goes to the sensible cooling load making up 99% of the annual energy load with no heating required and only 1% for dehumidification. This amounts to a total annual energy load of 119.27 MWh (119,270 kWh). It was verified against the quoted case in literature, which reported an annual energy load of 119,700 kWh, noting a discrepancy of around 0.4% only. The breakdown of the sensible cooling load showed how the building envelope-related gains (59%) outweighed the internal load (41%). They were led by conduction gains from the opaque and translucent elements (27%), followed by solar gains through glazing (19%), and infiltration (13%). The conduction gains signify the thermal performance of the elements (i.e., u-values and SHGC) with respect to climate conditions (i.e., outdoor temperature and relative humidity). The walls were found to propagate the highest conduction gains (31.7%), followed by the roof (27.9%), exposed ground floor (23.9%), windows (16.1%), and door (0.4%). This is likely to do with their surface areas more than their specific thermal performance, given that their corresponding u-values, in Table 4, indicated otherwise (the walls have the lowest u-values/the highest thermal efficiency). Regardless, it highlights where the focus should be targeted in performance improvement. With the combined share of the solar and conduction gains of glazing, the impact of their improvement rises.

When analysing the monthly cooling load, an alignment with the average external temperatures prevails, seen in Figure 9, where a peak cooling load is reached in the hottest month of the year (August). The peak of 55.03 kW occurs at 15:30, about more than three hours after the usual hottest period of day (around noon), which suggests a lag effect due to the building envelope’s thermal mass. This may justify why there is no heating load even when the external temperature drops below the heating setpoint during cooler nights, besides the effect of the internal gains and load distribution related to the user profile.

![Figure 9. Monthly cooling and dehumidification load against average external temperatures in Riyadh.](image)
4.2. Upgraded Model Assessment

This model was created to formulate the SBC performance benchmark representing the energy reduction target. When contrasting the baseline against the upgraded model, a similar load distribution prevails, where cooling and dehumidification make up the total energy load. However, the upgraded model consumes 103.92 MWh annually, which is 12.9% lower than the baseline case. The estimated aggregated consumption benchmark ($q_{SBC} = 197.94$ kWh/m$^2$) is lower than the baseline (227.18 kWh/m$^2$) by 29.24 kWh/m$^2$ (12.9%). The peak cooling load occurred in the same month/time of day but was lower by 10.8% at 49.14 kW. The solar gains are more than halved (−55%), and the conduction gains are lower by 10.3%. This highlights the higher significance of improving the fenestration’s thermal efficiency. When assessing the conduction gain breakdown, shown in Table 13, the weak performing elements are the external walls, roof, and fenestration. These correlate with their thermal performance, as they are the elements that failed to achieve the minimal U-value requirements. This suggests the validity of this building performance analysis method as an alternative to the more common method that seeks to improve each element at a time. This flexible approach can encourage designers to adopt more creative yet effective strategies when striving to achieve the SBC target.

| ELEMENT       | CONDUCTION GAINS | Differences (Reference to Baseline) |
|---------------|-----------------|-----------------------------------|
|               | Baseline (MWh)  | Upgrade (MWh)                     |                                  |
| Roof          | 8.85            | 5.33                              | −40%                             |
| Exposed floor | 7.59            | 7.59                              | −                                  |
| External walls| 10.04           | 6.70                              | −33%                             |
| Fenestration  | 5.10            | 3.96                              | −22%                             |
| Door          | 0.14            | 0.14                              | −                                  |

4.3. Single-Strategy Energy Performance

When testing the proposed strategies individually, the remaining design parameters were kept constant to that of the baseline model for fair comparison and the isolation of each modification’s contribution. The strategies were plotted against the $q_{SBC}$ benchmark to observe whether any of them had met the target individually, as demonstrated in Figure 10. The set of results revealed that only the designed rooftop PV system (M1) was able to meet the target at 194.44 kWh/m$^2$. This reassures the need for adopting a more holistic approach for retrofit programmes that target the improvement of more than one element at a time. Nevertheless, it should be noted that the fenestration-based strategies were the closest to meeting the target, followed by the walls and roof. The closest strategy was the double-glazing system with reflective low-E surfaces and argon-filled cavity plus overhangs (F3) at 203.69 kWh/m$^2$. The least effective was the green courtyard (L1) at 226.04 kWh/m$^2$. Figure 11 demonstrates their impact on the annual cooling load with respect to the baseline model to assess their performance on an element basis. The shortest column (highest cooling reduction) signifies the most effective strategy. In some cases, the performance was very similar (e.g., reflective cool roof (R1) and a green roof with integrated insulation (R3(a))). Thus, additional considerations had to be taken during the elimination process, as discussed later in Section 4.3.3.
The aggregated cooling and dehumidification load of the single strategies against the SBC benchmark.

Figure 10. The aggregated cooling and dehumidification load of the single strategies against the SBC benchmark.

Figure 11. The single-strategy impact on the annual cooling load in kWh (referenced to the baseline model), (A) Walls, (B) Fenestration, (C) Microgeneration, (D) Roof, (E) Landscaping.

4.3.1. External Walls: W1

The best option from the wall modification strategies based on an annual cooling load reduction of 6.1% was W3. Results revealed that a reflective coating on the walls alone was not able to compensate for the slashed insulation thickness of 50 mm (W2). Yet, when combined with an airtight building fabric, it was able to deliver and exceed the performance of a 100 mm (external) insulation board (W1). This was mainly because of a reduction of 27.7% in infiltration gains. Although W3 scored the least reduction in conduction gains (48%), see Figure 12, it reduced the peak cooling load by 5.4% compared to 3.0% and 2.5% from W1 and W2, respectively.
4.3.2. Fenestration: F1 versus F3

At first glance, F3 might seem like the more effective option. However, F3 covers F1’s energy reduction contribution (F1+overhangs), which means that essentially the overhangs contribute to only a 0.4% reduction (to 10.3% form 9.9%). Therefore, the integration of shading devices, in this case, was deemed ineffective. The results suggest that the glazing surface reflectance (F1) is more effective than its thickness (F2) in reducing solar gains and cooling load (SHGC > U-Value). Table 14 lists the tested glazing system’s properties. When assessing the conduction gains, or the heat transfer due to temperature differential between internal and external glazing sides, F3’s results revealed that the overhangs reversed 86% of the reduction effect from the reflective double-glazing system. This is as, for the same glazing specifications, F1 reduced 20.1% of the conduction gains while F3 dropped it by 2.8% only. The triple glazing (F2) was the most effective in reducing the conduction gains (43.7% drop) as it attained the highest glazing thickness. Overall, F1 was selected as the most effective strategy for maximising the annual cooling load reduction.

Table 14. Glazing system’s properties.

| Code                        | F1/F3       | F2         |
|-----------------------------|-------------|------------|
| U-Value (W/m²K)             | 2.651       | 1.876      |
| SHGC (-)                    | 1.185       | 0.618      |
| Thickness (mm)              | 24 mm (pane: 6 mm × 2/cavity: 12 mm) | 42 mm (pane: 6 mm × 3/cavities: 12 mm × 2) |

To finalise their overall performance, the strategy’s impact on daylight needs to be assessed, as explained in Section 3.2.5, by quantifying the average daylighting factor (DF<sub>AVC</sub>). Table 15 displays the results for both floors revealing how only F1 resulted in reasonable ranges (1.5% and 2% ideally). F2 showcases how increasing glazing thickness might not necessarily affect the amount of daylight entering the space to that extent. The baseline case did not clarify the existing glazing reflectance and transmittance properties, however considering the climate type with its typically clear skies, it can be assumed that its DF<sub>AVC</sub> is closer to that of F2 out of the three. As for that of F3, when combining both the shading device and manipulating transmittance and reflective values, the result is a rather dark and dull indoor space that is likely to increase the artificial lighting demand and cancel the energy savings retrieved from its heat gain reduction ability. Perhaps, in the case of a non-passive retrofitting model, the employment of an adaptive lighting arrangement with the assistance of a more sophisticated building management control system can be useful to further optimise the strategies. Overall, F1 was favoured as it delivers the best trade-off between heat gain reduction and daylight access from the three tested options.
Table 15. Average daylighting factors for \( G_f \) and \( f_1 \) with F1, F2, and F3.

|       | F1  |       | F2  |       | F3  |       |
|-------|-----|-------|-----|-------|-----|-------|
|       | \( G_f \) | \( f_1 \) | \( G_f \) | \( f_1 \) | \( G_f \) | \( f_1 \) |
| \( DF_{AVG} \) | 2.18% | 1.53% | 4.50% | 3.16% | 1.24% | 0.87% |

4.3.3. Roof: R1 versus R3(a)

Many of the roof optimisation strategies showed a relatively low reduction effect, ranging between \(-0.2\%\) to \(-1.7\%\), except for the cool roof model (R1) and the green roof with insulation (R3(a)). Both delivered very similar energy savings potential, with R3(a) performing slightly better (+0.3\%). This implied the need for considering other factors during the selection, which raises questions about the limitations of relying solely on energy savings during the elimination decision-making process. A potential suggestion can be the earlier consideration of the cost factor. However, scaling over the large sample size of individual strategies can be unnecessarily tedious at an early stage. This is where the discussed significance of design know-how and customer preferences prevail. Referring to the literature review, both R1 and R3(a) require maintenance, but the former needs it at a lower frequency and would not require specialised labour. Also, the novelty factor of green roofs in KSA makes their installation and maintenance more challenging with respect to the simpler and more traditional alternative of a lighter-coloured roof. Thus, implying the general tendency of R1 to be the low-cost alternative, which outweighs the small energy-saving discrepancy. Besides, it should be noted that the green roof technology within itself without insulation (R3(b)) only delivered less than half (\(-1.3\%)\) of the reduction capability of R1 (\(-3.2\%\)).

When evaluating the other alternatives (flying roof (R2) and green roof without insulation(R3(b))), though not as effective, they can deliver other indirect merits that relate to reducing heat fluctuations across the roof system. Thus, leading to higher longevity and can translate to fewer maintenance costs. They reduced the conduction gains by 35\% and 16\%, respectively. The least effective shading strategy was the indirect effect of the rooftop PV system (R4). Despite masking a similar roof area as the other roof shading strategies, it only resulted in a 2\% reduction in conduction gains and 0.2\% in cooling load. Furthermore, the significantly lower heat gains through the flying roof imply the need to minimise the deployment of flat roof systems in new builds (see Figure 13). The results also discredit the green roof system’s (without insulation) effectiveness relative to the other strategies.

![Figure 13. Flying roof shading effect on the summer solstice at noon.](image)

4.3.4. Microgeneration: Shading Versus Generation (M1)

Among the three PV solutions, the rooftop arrangement resulted in the highest cooling load reduction (\(-14.4\%\)) mainly due to its generation output rather than the indirect shading potential. M2 displayed a relatively comparable performance (\(-10.2\%)\) despite having a smaller system capacity, which presents the combination of tilted BIPV shading as a potentially attractive alternative to the more common rooftop systems in KSA. However, the PV window arrangement, in this case, was not successful (\(-0.9\%)\) due to the vertical placement of the BIPV cells, which is highly unfavourable relative to the location’s vertical solar irradiance. Although its considerable solar gains reduction (\(-54.1\%)\) presents an
opening for further research to determine a potential optimisation technique tailored to KSA’s solar geometry (see thermal diagrams in Appendix B).

Three variants of M1 were tested based on different shading factors (15%, 30%, and 45%) of the accessible roof area, where the latter was the maximum possible ratio based on the assumptions in Section 3.2.7. The results, in Figure 14, showed that a minor discrepancy was observed in its influence on heat gains/cooling load reduction. The 45% arrangement was used in the relative comparison between the roof shading strategies in Section 4.3.3 to ensure a fair comparison by keeping a similar roof coverage range. The 30% arrangement was selected for the generation output comparison (in Figure 10) as it was the minimal size to meet the benchmark.

![Figure 14](pv_vs_generation.png)

**Figure 14.** Shading versus generation output of three M1 system sizes.

4.3.5. Landscaping: L1

As highlighted earlier, L1 was the least effective strategy in reducing the cooling load, but it succeeded in reducing the solar gains by 8%. This is due to the brief shading window towards the end of the day (late afternoon). Figure 15 shows the simulated landscape arrangement and its potential shading effect. There are also other non-energy-related benefits associated with a cooler and cleaner microclimate that can reflect positively on occupant satisfaction and health. No impact was recorded replacing surface material properties of the shading devices (L2) on the cooling load (L2 = F3). So, L1 was promoted for the second set of simulations.

![Figure 15](landscaping.png)

**Figure 15.** The selected landscaping design (a) and its shading impact at (b) Summer Solstice (at 17:00), (c) Winter Solstice (at 15:00), (d) Equinox (at 17:00).
4.3.6. Section Overview: The Selection and Formulation of the Retrofit Packages

After the considered arguments in the previous sub-sections, the following strategies (in Table 16) were selected as the top-performing alternatives and used to formulate different combinations of retrofit packages for further testing.

Table 16. The selected top performing single retrofit strategies.

| Target Element (Code) | Reviewed Description                                                                 | Percentage Reduction |
|-----------------------|--------------------------------------------------------------------------------------|----------------------|
| External walls (W3)   | Envelope airtightness of 0.5 ach and reflective wall coating with an albedo 0.6.     | −6.1%                |
| Fenestration (F1)     | Double-glazing system with reflective low-E surface and an argon-filled cavity.      | −9.9%                |
| Roof (R1)             | Reflective roof coating with an albedo of 0.6.                                       | −3.2%                |
| Microgeneration (M1)  | South-facing rooftop PV array that covers 30% of the accessible roof area.           | −14.4%               |
| Landscaping (L1)      | Green courtyard with three wide-canopied tall trees covering the Western wall and a collection of shrubs surrounding the North-western side. | −0.5%                |

The corresponding nine unique combinations that were simulated are presented in Figure 16.

![Figure 16](image)

Figure 16. The formulated combinations of the selected best strategies.

4.4. Energy Performance of Retrofit Packages

The formulated retrofit packages were plotted against the SBC benchmark, as illustrated in Figure 17. These revealed that all combinations were able to meet and/or pass the benchmark except for R1W3L1. The three most effective packages relative to the baseline model were W3F1M1 (−30%), M1R1F1 (−27%), and F1L1M1 (−24%; the percentage reduction is with reference to the baseline model). All of which incorporated the improved glazing (F1) and the rooftop PV system (M1). This implies the significant role of solar gains reduction and renewable energy in a Riyadh-based retrofitting programme. The only package that incorporated the main three building fabric strategies (without PV), W3R1F1, was able to achieve a 19% reduction, which is a comparable performance. The peak cooling load reductions mirrored the discussed pattern, which reaffirms a synergy between PV generation and consumption patterns.
Buildings 2021, 11, x FOR PEER REVIEW ... W3R1M1 M1R1F1 W3R1F1
Annual Solar gains (MWh)
Upgraded model: 10.16MWh
−76% −79%
−79% −7% 0%
−78% −78%
Baseline W3F1M1 W3L1M1 F1L1M1 R1M1L1 R1F1L1 R1W3L1 W3R1M1 M1R1F1 W3R1F1

Figure 17. Comparative analysis of the energy performance of the retrofitting packages.

On a final note, Figure 18 verifies the strong correlation between reducing solar gains and meeting the SBC benchmark, where the best performing from a cooling load reduction perspective were the combinations that managed to slash the solar gains significantly.

![Figure 18. Solar gains of the retrofit packages.](image)

5. Conclusions and Further Recommendations

5.1. Conclusive Statement

This two-part study aimed to propose a holistic retrofit approach for Saudi designers to facilitate the identification of optimisation solutions as potential candidates for a Riyadh-based retrofit programme. The study covered the merits of using the whole system modelling approach that captures the dynamic interaction between the subsystems of a building using IES-VE. It has successfully delivered the study’s objectives, as follows:

Objective 1: Based on the selected archetypical baseline building model, the performance gap was nearly 13% higher than the set SBC benchmark. The purpose was to display the validity of the proposed whole-building analysis method as an alternative to the more common approach that seeks to improve one element at a time. The flexibility of this method can encourage designers to adopt a wider combination of strategies when striving to achieve the target rather than recommending a specific energy reduction target.

Objectives 2 and 3: In this study, the best-performing strategies shared a common theme of solar gain reduction with the fenestration-based strategies (i.e., double-glazing system with low-E surfaces and argon-filled cavity) outperforming the remaining strategies for Riyadh’s climate conditions. None of them were individually capable of meeting the SBC target except for the rooftop PV system, which was deemed to be an instrumental tool for its energy generation capability, and in improving the overall effectiveness of the retrofit packages. The best of which linked a glazing strategy (F1) and a rooftop PV system (M1).

5.2. Research Limitations and Further Recommendations

These results are indicative rather than prescriptive. This stems back from the following reasons, which can also be taken as a window for future research. Firstly, buildings
are dynamic, meaning the results are subject to variance in different baseline conditions, noting that the design approach remains valid. The baseline model’s performance is subject to error related to the ambiguous user-profiles and generic floor plans of internal zones suggested in the reviewed literature. There is also uncertainty around the rebound effect after applying the retrofit packages due to unpredictable user behaviour. Finally, a financial perspective on the viability of the strategies individually and in packages plus their sensitivity to the current and future economic landscapes would be highly useful to the decision-making process. A potential way would be through performing a lifecycle cost (LCC) analysis for a holistic lifetime view over such projects. Though the lack of a reliable cost database may discourage organisations from adopting the LCC method, in turn, miss out on the insight and time-saving benefits that it can provide to the decision-making process. Also, it should be indicated that the socio-cultural aspects were not investigated in detail, as further data collection may be required through surveys that can be performed in future studies, noting the beneficial insight it can provide for the successful delivery of such programmes.

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Appendix A. Supporting Data

Table A1. Building Envelope Requirements for Zone 1 [11].

| Opaque Elements | Residential Conditioned | Residential Unconditioned |
|-----------------|-------------------------|---------------------------|
|                 | Assembly | Insulation | Assembly | Insulation |
|                 | Max U-Value W/m² °C | Min R-Value m² °C/W | Max U-Value W/m² °C | Min R-Value m² °C/W |
| Roofs           | Insulation Entirely Above Deck (Continuous Insulation) | U-0.202 | R-5.0 C.I. | U-0.4 | R-2.5 C.I. |
| Wall            | Above-Grade Mass (Continuous Insulation) | U-0.342 | R-2.92 C.I. | U-0.453 | R-2.2 C.I. |
|                 | Below-Grade | C-0.678 | R-1.3 C.I. | C-6.473 | NR |
| Floors          | Mass | U-0.496 | R-1.5 C.I. | U-0.78 | R-0.7 C.I. |
|                 | Steel-Joist | U-0.296 | R-3.3 | U-0.296 | R-3.3 |
|                 | Other | U-0.188 | R-5.3 | U-0.288 | R-3.3 |
|                 | Slab-on-Grade Floors | F-0.90 | R-2.6 | F-1.263 | NR |
| Doors For 60 cm | All Assemblies | U-2.839 | U-2.839 |
Table A2. Fenestration for zone 1, 2 and 3 [11].

| Fenestration | Assembly | Assembly | Assembly | Assembly |
|--------------|----------|----------|----------|----------|
|              | Max U-Value W/m² °C | Maximum SHGC | Max U-Value W/m² °C | Maximum SHGC |
| Vertical Glazing, 25% of Wall All Assemblies | U-2.668 | SHGC-0.25 | U-3.695 | NR |
| Skylight with Curb, Glass, % of Roof 0–3% All Types | U-4.259 | SHGC-0.35 | U-10.22 | SHGC-0.35 |
| Building Air Tightness | (ACH50) 4.0 | | NR | |

Appendix B. Additional Methodology Considerations

Table A3. Rooftop PV Design Variants.

| ROOF AREA (m²) | PV PANEL SIZE (m²) | CAPACITY (Wp) | V_{mpp} (V) | V_{DC} (V) |
|----------------|-------------------|---------------|-------------|------------|
| 157.50         | 1.63              | 310           | 33.25       | 90–450     |
| Shading factors | 15%               | 23.63         | 0.25        | 70.88      |
| Covered area (m²) | 4.34              | 14            | 28          | 41         |
| No. of panels | 14                 | 3.26          | 6.51        | 9.53       |
| System size (kWp) | 2 x 7              | 2 x 14        | 13 x 3      | 63.45      |
| Inverter size (kW) | 22.78             | 45.55         | 40%         |
| Actual no. of panels | 14                | 14            | 14          | 14         |
| Actual area (m²) | 39                 | 40%           | 40%         | 40%        |

Covered ratio without spacing between panels

Figure A1. The thermal diagram of the rooftop PV variants.
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