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Early-Stage Design and Energy Performance Analysis of Residential Buildings in Hot–Arid Climates Using BIM-Based Modeling Tools

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Abstract

Building energy performance is largely determined during the early conceptual design stages. However, energy evaluation is often postponed until after key architectural decisions—such as massing and façade configuration—have been finalized, limiting opportunities for meaningful optimization. This study addresses this gap by demonstrating a Building Information Modeling (BIM)-based comparative approach for integrating energy analysis into early design stages. Focusing on residential villas in Abu Dhabi, UAE, three residential forms were selected for testing: compact, L-shaped, and U-shaped designs. Each form included multiple iterations representing the design progression process, namely the base building form, façade refinement (glazing and shading adjustments), and spatial layout and/or orientation adjustments. The analysis incorporated variations in glazing ratio and building orientation to evaluate their combined impact on Energy Use Intensity (EUI). Among the tested options, the L-shaped configuration achieved the lowest EUI (79 kWh/m^2), representing the best-performing option, followed by the compact (81 kWh/m^2) and U-shaped (82 kWh/m^2) configurations. The results also confirm that orientation remains an important factor even after façade refinement. Overall, the findings suggest that BIM-based energy analysis is most effective when applied early as a comparative and iterative design-support tool.

Keywords: BIM; building energy performance; early-stage design; residential villa; Energy Use Intensity; Autodesk Revit; Abu Dhabi; hot–arid climate; massing design; sustainable architecture

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Academic Editor: Nina Szczepanik-Scislo

Received: 28 April 2026

Revised: 1 June 2026

Accepted: 8 June 2026

Published: 11 June 2026

1. Introduction

The building sector is responsible for approximately 36–40% of the global energy consumption. It is also responsible for nearly one-third of greenhouse gas emissions. This creates a critical issue that requires improvement in terms of sustainability and environmental impact [1,2]. In this connection, it is necessary to enhance the energy efficiency of buildings and introduce sustainability considerations in the design process, especially decisions that are related to orientation, building form, envelope materials, and glazing ratio and are made early in the project. These decisions can strongly influence long-term operational efficiency [3], as early-stage design parameters significantly affect thermal performance and energy demand [4].

There have been significant changes within the Architecture, Engineering, and Construction (AEC) industry due to the development of Building Information Modeling (BIM). As the construction industry works to lower energy consumption across a building's entire life cycle, architects and engineers need tools that can deliver fast, accurate, and easy-to-understand feedback during the earliest phases of design [5]. The integration of digital models with advanced data analytics is emerging as a major focus in the construction industry and across other technology-driven sectors [6]. This change is due to the integration of design, documentation, and analysis within a single platform. For example, Autodesk Revit is a widely used software in the BIM field. It includes built-in features that evaluate performance indicators, including solar analysis and daylight performance [7], as well as external plug-ins that can be used within the software. Previous studies have shown that BIM-based energy analysis can support better design decisions by enabling the comparison of alternative design options [8] and facilitating data-rich simulation environments for iterative design refinement and performance evaluation [9].

Previous studies have shown that BIM can improve building energy efficiency by integrating performance analysis into the design process, allowing critical decisions to be evaluated before they become difficult to modify [3,10,11]. Sofronievska et al.'s findings also suggest that BIM technology improves the energy efficiency of buildings through its capability to compare design alternatives in one digital environment [7]. In addition, the review by Kamel of the application of BIM technology in energy simulation concludes that BIM is an effective tool to improve the assessment of decision-making; however, its implementation has been inconsistent [8]. However, although the previous literature demonstrates the importance of BIM, traditional simulation methods, although accurate, tend to require substantial data and are not well suited for use during the conceptual phase, when multiple design options are being explored and refined. Furthermore, energy analysis is often introduced only after major design decisions have already been finalized in many conventional design workflows, which limits the opportunity for effective iterative refinement [12].

Hence, the present study investigates how BIM tools can be applied in the design phase to analyze the model energy performance at an early stage of residential villas. The study aims to demonstrate practical methods for architects and designers to enhance and upgrade the initial design concept stage by introducing energy performance analysis. The findings aim to provide a structure for integrating BIM-based energy analysis into early design.

To achieve the study's aim, a research-by-design methodology was adopted. In this approach, the architectural design process serves as a means of generating new insights, knowledge, practices, and outcomes, fostering critical inquiry through the act of designing itself [13]. Therefore, the outcomes of this approach can guide industry professionals in implementing BIM for early-stage building energy performance analysis, thereby helping to overcome key design-stage barriers such as a shortage of skilled and experienced personnel, limited understanding of BIM, insufficient exposure to BIM concepts, and low awareness of its benefits [14,15].

The study focuses on supporting the adoption of BIM in early-stage conceptual design, where building massing is a key task. During this stage, architects explore spatial and formal configurations while considering constraints such as floor area and regulatory requirements [16]. Designer–client collaboration is also a crucial part of this phase, involving interaction between the architect, the client, and the evolving design. At this stage, both parties work together to reach an agreement on specific design models [17]. The selected case considers the hot–arid climate of the United Arab Emirates, with a focus on the city of Abu Dhabi. Electricity consumption per capita in Abu Dhabi ranks among the highest globally, with air conditioning in the residential sector accounting for a significant portion of this demand [18]. Improving building design is essential for reducing energy consumption in buildings located in hot–arid climates, where cooling requirements are particularly high [19]. Hence, the literature has highlighted the potential of simulation-based analysis for optimizing building design strategies to create energy-efficient and sustainable buildings in arid and semi-arid regions, including reducing cooling demand and overall life-cycle energy consumption [20]. This is because parametric simulation offers a highly adaptable approach for optimizing early-stage building designs in hot–arid climates [21].

Section 2 outlines the materials and methods used to achieve the study aim, which include the research design and approach, a case study, tools and parameters, scenarios, data collection, and analysis. Section 3 presents the results of the various scenarios and provides a comparative analysis. Section 4 provides discussion, interpretations, and future implications. Finally, the study is concluded in Section 5.

While previous studies have established the general value of BIM-based energy analysis for sustainable design, the novelty of this study lies in four main aspects. First, the research provides a direct comparative evaluation of compact, L-shaped, and U-shaped residential villa massing configurations under the same climatic, material, and operational conditions within the hot–arid context of Abu Dhabi. Second, the study applies a simplified BIM-based workflow using Autodesk Revit 2026 and Enscape Impact specifically as an early-stage comparative decision-support framework rather than as a detailed engineering simulation environment. Third, the research combines multiple performance indicators within a single iterative workflow, including Energy Use Intensity (EUI), operational carbon emissions, daylight distribution, and orientation sensitivity. Finally, the study demonstrates how iterative architectural refinements involving glazing ratio, shading, spatial organization, and orientation can be systematically evaluated during conceptual design using accessible BIM-based tools commonly used in architectural practice.

2. Materials and Methods

To investigate how BIM tools can be applied during the design phase to support early-stage energy performance assessment, a research-by-design methodology was adopted to generate insights, knowledge, and practices that support practitioners. Section 2.1 presents the research approach, while Section 2.2 describes the case study and climatic context. Sections 2.3 and 2.4 outline tools and parameters, and the scenarios, respectively. Finally, Section 2.5 describes data collection and analysis.

2.1. Research Design and Approach

This research consists of mixed-methods of design and combines quantitative energy-simulation analysis with interpretation of the design outcomes to evaluate how BIM-based modeling supports energy-efficient building design in the UAE context. Moreover, it follows a design-science framework, as the knowledge or information is generated through creating a model derived from the Estidama Pearl Building Rating System (PBRS), testing it, and evaluating it in terms of energy performance. The design process is organized within a scenario-iteration framework, which is created using Autodesk Revit 2026. Three main architectural scenarios were defined, each of which corresponds to a different massing approach for a single-family residential villa in Abu Dhabi. For each scenario, three design iterations were created through a series of incremental changes to the geometric form, façade, and spatial organization of the building, while keeping the gross floor area, material properties, and building systems constant. This method helps the researcher differentiate between the impact of architectural design decisions and building energy performance. Energy analyses were conducted using the built-in analysis tool in Revit and Enscape Impact, and results such as annual energy use, Energy Use Intensity (EUI), and cooling load were generated.

2.2. Case Study and Climatic Context

The UAE is characterized by a hot desert climate, where the average annual air temperature exceeds 27 °C [22], whereas the humidity levels fluctuate from ~50% in winter to over 70–90% in summer (coastal UAE) [23]. This leads to extensive use of air conditioning. For example, the cooling load is responsible for more than 70% of the building's total electricity demand [24]. Due to this extensive use, it is important to take into consideration the design decisions during the design stage.

The case study therefore acts as a digital experiment that represents a locally relevant building typology under the climate and regulatory conditions of the region. This makes the sensitivity testing of the design transparent. Moreover, the selection of the UAE climatic context provides more scientific relevance and supports the goal of this research, which is to enhance energy-efficient building design through BIM-based modeling.

2.3. Simulation Tools and Fixed Parameters

The energy simulations were conducted through Autodesk Revit 2026 software with the use of Enscape Impact as the primary tool for evaluating building performance at the conceptual stage. Autodesk Revit was used in the generation of all of the architectural models in all iterations and the creation of models for conducting simulations. The climate data for Abu Dhabi was used in all simulations to match the climatic conditions of the project site. In order to provide a balanced comparison, variables that remain constant throughout the simulation were established in all iterations. Building envelope thermal properties were based on the Estidama and ASHRAE benchmark values for hot residential buildings.

This simulation workflow is intended for comparative early-stage design analysis rather than final engineering prediction. The building system assumptions remain simplified at this stage; therefore, the results are most reliable for evaluating relative design performance between options, while detailed HVAC sizing and peak-load calculations would require more advanced simulation tools and a fully developed system design.

A previous comparison study by Aljundi et al. [25] reported differences between simplified BIM-based simulation workflows and more detailed engines such as EnergyPlus. For example, the study found that Revit generally overpredicted heating demand by about five times and cooling demand by about 2.5 times compared with EnergyPlus, which was linked to simplified treatment of internal heat gains and thermal inertia. Therefore, in this study, the Revit-based workflow is used mainly as a comparative early-stage design-support tool rather than as a source of final detailed load prediction [25].

For consistency across all simulations, the gross floor area was maintained at approximately 430 m^2, the Solar Heat Gain Coefficient (SHGC) of the glazing was fixed, Abu Dhabi climate data were used for all models, and the building systems, internal loads, and occupancy schedules remained under the default assumptions applied by Enscape Impact. The spatial diagram was also kept consistent across the scenarios so that the differences in the results could be attributed mainly to changes in massing, glazing ratio, shading, and orientation.

The simulation assumptions summarized in Table 1 were maintained consistently across all scenarios to ensure a controlled comparative evaluation of architectural design

https://doi.org/10.3390/buildings16122329

variables. The study intentionally adopted simplified early-stage assumptions provided by Enscape Impact because the objective was to compare relative design performance during conceptual design rather than to generate final compliance-level engineering predictions. Consequently, the workflow is intended as an iterative design-support framework for evaluating the influence of massing, glazing ratio, shading, spatial organization, and orientation under fixed operational conditions.

Table 1. Fixed simulation assumptions and design parameters used across all scenarios.

Parameter Category	Description/Value
Software Platform	Autodesk Revit 2026 + Enscape Impact
Climate File	Abu Dhabi, UAE (hot–arid climate)
Building Typology	Two-story residential villa
Gross Floor Area (GFA)	~430 m^2 (constant across all scenarios)
HVAC Assumptions	Default Enscape Impact system assumptions
Occupancy Schedules	Default residential occupancy schedules within Enscape Impact
Internal Loads	Default Enscape Impact residential assumptions
Cooling Setpoint	Default Enscape Impact residential cooling assumptions
Envelope Wall U-Value	0.3818 $W/m^2 \cdot K$
Roof U-Value	0.2003 $W/m^2 \cdot K$
Floor U-Value	0.3133 $W/m^2 \cdot K$
Glazing U-Value	1.9873 $W/m^2 \cdot K$
SHGC	0.24
Scenario 1 WWR	Iteration 1: 30.61%; Iteration 2: 22.26%; Iteration 3: 9.29%
Scenario 2 WWR	Iteration 1: 25.10%; Iteration 2: 20.56%; Iteration 3: 20.56%
Scenario 3 WWR	Iteration 1: 23.66%; Iteration 2: 21.49%; Iteration 3: 21.49%
Orientation Testing	Scenario 2 mirrored; Scenario 3 rotated 180°
Fixed Parameters Across All Models	Material properties, climate conditions, occupancy assumptions, HVAC assumptions, and gross floor area
Main Evaluated Outputs	EUI, annual energy use, operational carbon emissions, daylight distribution, and cooling energy share

The performance indicators used in this study were derived from the simulation outputs generated through the BIM-based workflow. Energy Use Intensity (EUI) was calculated as:

$$EUI = \frac{E_{annual}}{A}$$

where E_{annual} represents the annual building energy consumption (kWh/year) and A represents the gross floor area (m^2).

Operational carbon emissions were estimated based on the annual operational energy consumption:

$$CO_{2,\,op} = E_{annual} \times EF$$

where $CO_{2,op}$ is the annual operational carbon emissions (kgCO_2/year) and EF is the electricity emission factor used within the simulation environment.

Window-to-wall ratio (WWR) was defined as:

$$WWR = \frac{A_w}{A_f}$$

where A_w is the total glazing area and A_f is the total façade area.

The Solar Heat Gain Coefficient (SHGC) represents the fraction of incident solar radiation transmitted through the glazing system and was maintained constant across all scenarios to ensure controlled comparative analysis.

2.4. Scenario Development and Iterative Testing

Three residential forms were chosen for testing, which consisted of compact, L-form, and U-form designs. The three forms included three iterations each, which constituted the design progression process that is normally followed by designers at an early stage. For the first iteration, the design was completed using the base form, while for the second iteration, the focus was on façade detailing, mainly involving changes in glazing and shading aspects. The refinement process followed a comparative iterative approach in which glazing ratios and shading configurations were progressively adjusted based on the performance outcomes of the previous iteration, particularly targeting reductions in solar heat gains and cooling demand. At the end of the third iteration, the main trends of performance were known, and additional iterations would probably have no further effect.

To clarify the research algorithm, the scenario–iteration process was structured step by step across all massing configurations. First, three baseline massing configurations were developed: compact, L-shaped, and U-shaped. Second, the main control variables were fixed across all models, including gross floor area, envelope thermal properties, glazing SHGC, climate data, building systems, occupancy schedules, and internal load assumptions. Third, Iteration 1 represented the base form for each massing configuration. Fourth, Iteration 2 introduced façade refinement through glazing-ratio reduction and shading adjustment. Fifth, Iteration 3 tested either further planning refinement or orientation sensitivity: in the compact scenario, spatial layout and shading were refined further, while in the L-shaped and U-shaped scenarios, the refined forms were mirrored or rotated to assess orientation sensitivity. Finally, all iterations were simulated using the same BIM-based workflow, and the results were compared using EUI, annual energy use, operational carbon emissions, cooling energy share, and daylight distribution.

2.5. Algorithm Description

Figure 1 presents a structured workflow for implementing BIM-based energy performance analysis during the early design stages. The process begins with defining key project characteristics as inputs for the development of the BIM model. These characteristics include climate data, building typology, and spatial requirements. Subsequently, a base BIM model is developed, after which key design scenarios are selected. Iterative design modifications are then performed, including glazing adjustments, shading integration, and orientation testing. Energy simulation tools within Revit, along with external plug-ins such as Enscape Impact, are subsequently used to generate performance indicators, including EUI, operational carbon impact, and daylight distribution. These outputs provide a basis for design evaluation and enable architects to refine the model through an iterative feedback loop.

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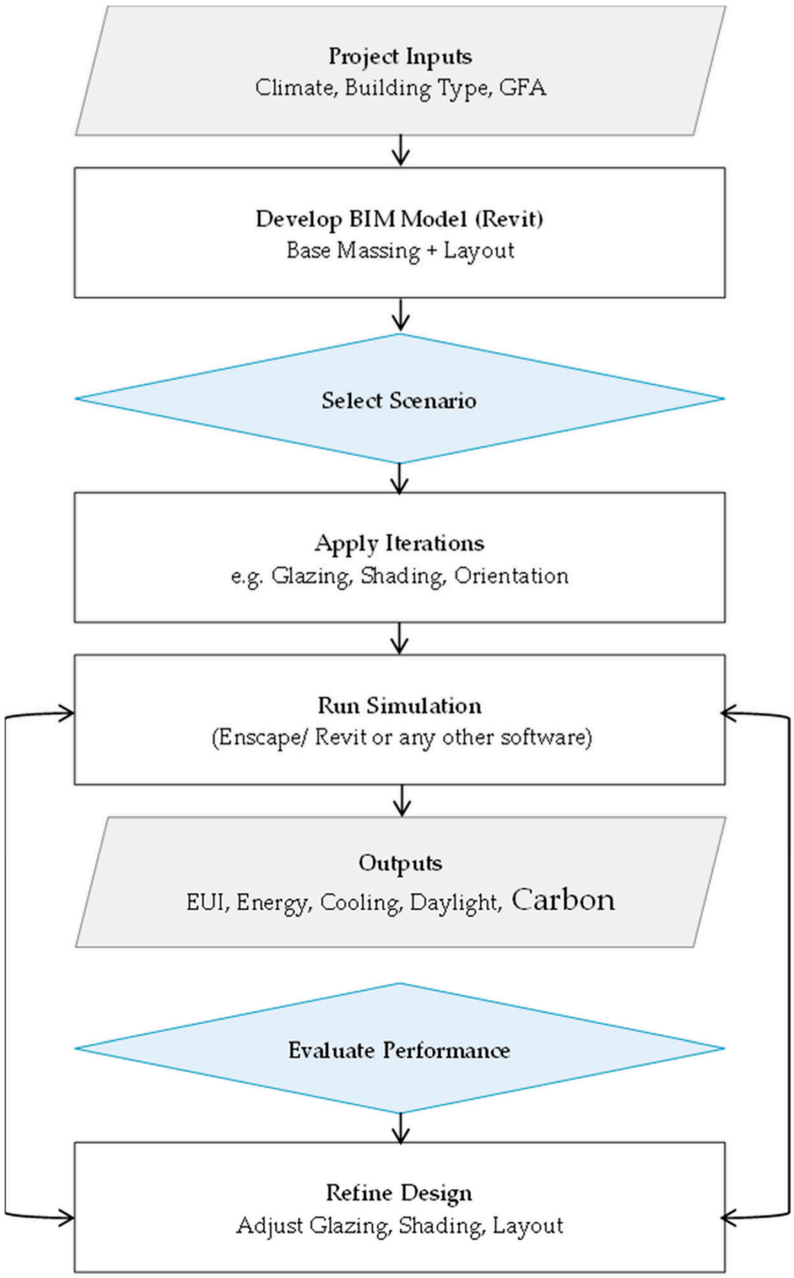


Figure 1. Algorithmic workflow for evaluating and refining early-stage residential building design using BIM-based energy simulation tools.

2.6. Data Collection and Analysis

Quantitative data were obtained through simulation for each round of the design process, specifically on EUI, cooling and heating loads, solar gains, and daylight factor. These data were exported from the simulation workflow and underwent both descriptive and comparative analyses. Considering that the floor area and climate remain fixed variables, any difference in results can be mainly attributed to different decisions made by architects in their designs. To quantify which scenario outperformed the others and by how much compared to the energy efficiency goal, quantitative analysis was performed. While this was underway, an interpretive design analysis was performed in parallel, examining how modifications in massing, glazing, shading, spatial configuration, and orientation affected the simulation results.

3. Results

The results of the energy simulation analysis for the three massing scenarios and their design iterations are discussed in this section. Furthermore, results are discussed under the compact (Section 3.1), L-shaped (Section 3.2), and U-shaped (Section 3.3) building massing configurations, followed by a comparative analysis of all scenarios together (Section 3.4). They show how early design refinements such as glazing ratio, shading, spatial layout, and orientation affect the building's energy performance. Figure 2 shows the massing development across the three scenarios and their iterations, which forms the basis for the analysis presented in this section.

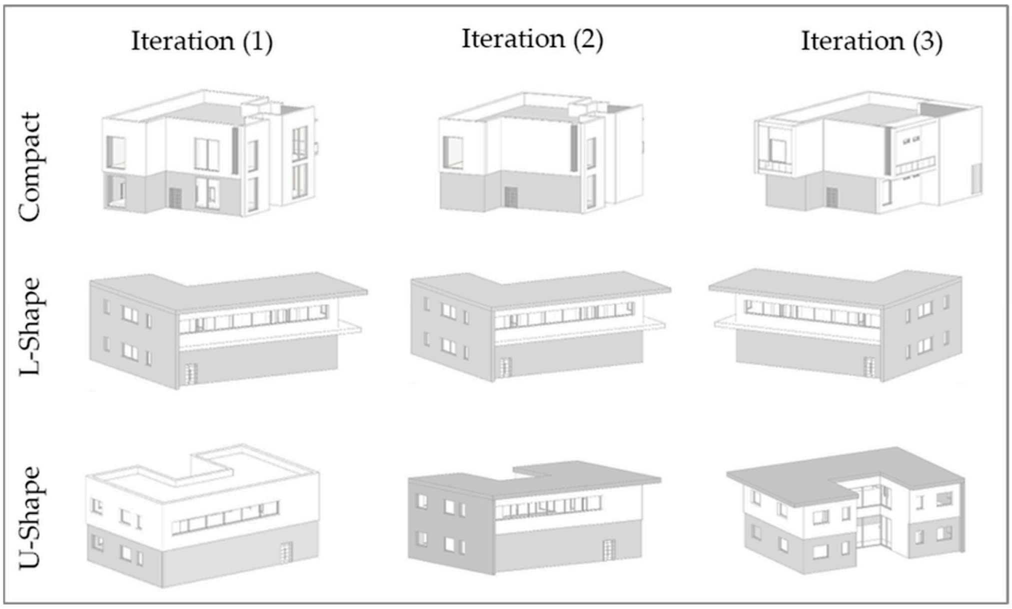
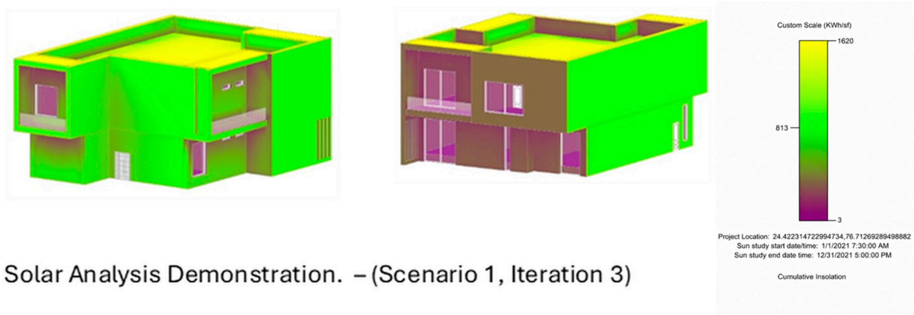


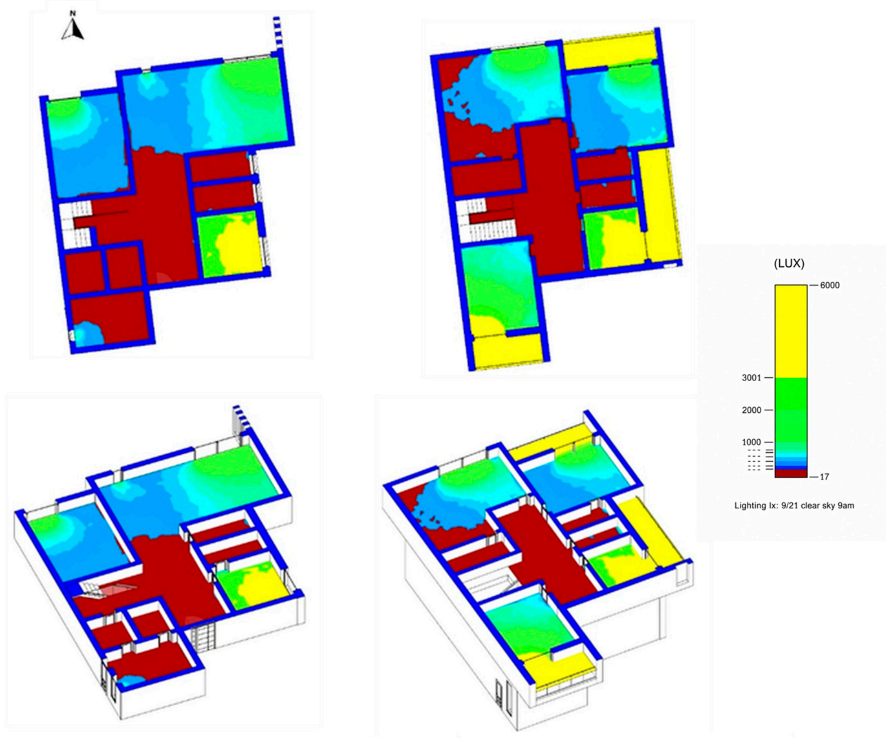
Figure 2. Massing development across the three scenarios.

3.1. Results of Compact Massing

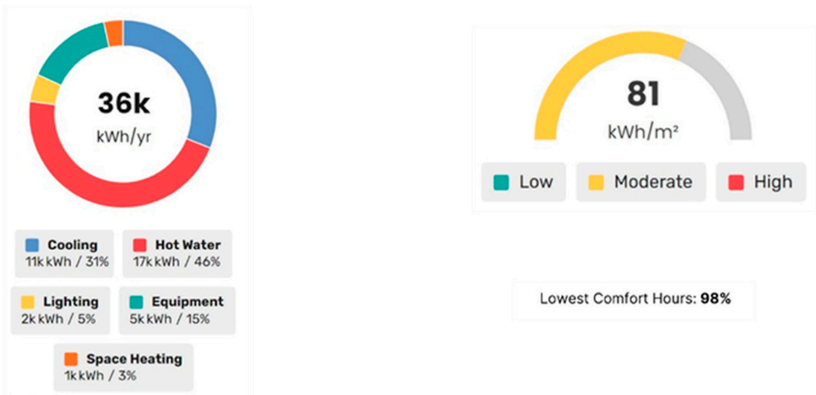
The first scenario evaluates the energy performance of a compact villa massing through three successive design iterations. The iterations involved progressive reductions in glazing ratio, integration of façade shading elements, and spatial layout refinements while maintaining constant material properties, floor area, occupancy assumptions, and building system settings. The results show a clear reduction in overall energy consumption and EUI from the first iteration to the third iteration. This aligns with the findings reported in [26], Raji 2017 which showed that decisions made during the early design stage can significantly affect building energy performance. It makes early evaluation essential for energy-efficient design [26]. Furthermore, these results provide clear evidence that architectural design alone has the potential to greatly decrease energy use and impact on the environment, especially when using the same materials and building systems. Figure 3 presents representative simulation outputs for the optimized compact massing scenario (Iteration 3), including solar exposure analysis, daylight distribution, and Enscape Impact energy simulation results. The figure illustrates how façade refinement, shading integration, and spatial iterative refinement influenced solar exposure, daylight penetration, and overall building energy performance within the BIM-based workflow adopted in this study. Table 2 shows the comparison between the three iterations.



a) Solar Analysis Demonstration. – (Scenario 1, Iteration 3)



b) Lighting Analysis Demonstration. – (Scenario 1, Iteration 3)



C) Energy Use Intensity (EUI) and Annual thermal comfort percentage. – (Scenario 1, Iteration 3)

Figure 3. Representative simulation outputs for the optimized compact massing scenario (Iteration 3): (**a**) solar exposure analysis, (**b**) daylight distribution, and (**c**) Enscape Impact energy simulation results.

Table 2. Comparative summary of annual energy use, EUI, cooling energy share, operational carbon emissions, and thermal comfort across the three iterations of Scenario 1.

Performance Indicator	Iteration 1	Iteration 2	Iteration 3	Change I1 → Best Iteration	% Change
Annual Energy Use (kWh/year)	43,000	39,000	36,000	7000 kWh	−16%
Energy Use Intensity (kWh/m^2·year)	101	91	81	20 kWh/m^2	−20%
Cooling Energy Share (%)	42%	38%	31%	11 points	−26%
Operational Carbon Emissions ($kgCO_2$/year)	7119	6494	6094	1025	−14%
Thermal Comfort (% of hours)	99%	99%	98%	1%	Negligible

3.2. Results of L-Shaped Massing

The L-shaped configuration alters the directional exposure of the façades by increasing the number of external surfaces and changing the orientation of glazed openings relative to solar radiation. For each of the three iterations, the design was progressively refined through façade adjustments and orientation testing while keeping consistent material properties, floor area, and building system assumptions. The results herein show that modifications to glazing ratio, shading strategies, and directional placement of the mass directly influenced cooling demand, EUI, and operational carbon performance. Overall, the L-shaped scenario demonstrates that architectural refinement can reduce energy use and carbon emissions using the same materials and fixed building system assumptions. Table 3 summarizes the comparison between all Scenario 2 iterations.

Table 3. Comparative summary of annual energy use, EUI, cooling energy share, operational carbon emissions, and thermal comfort across the three iterations of the L-shaped scenario.

Performance Indicator	Iteration 1	Iteration 2	Iteration 3	Change I1 → Best Iteration	% Change
Annual Energy Use (kWh/year)	41,000	37,000	39,000	4000	−9.8%
Energy Use Intensity (kWh/m^2·year)	88	79	83	9	−10.2%
Cooling Energy Share (%)	40%	40%	38%	−0	0%
Operational Carbon Emissions ($kgCO_2$/year)	6659	6003	6364	−656	−9.9%
Thermal Comfort (% of hours)	99%	99%	98%	0%	Negligible

3.3. Results of U-Shaped Massing

The U-shaped villa massing of the third scenario provides a more enclosed courtyard space compared to the L-shaped and compact scenarios. As discussed, the design process was refined over the three scenarios through façade changes and orientation tests, with consistent material properties, gross floor area, and building system. As shown, the results indicate that the changes to the glazing ratio, shading, and mass orientation impact cooling demand, energy intensity (EUI), and operational carbon emissions. However, unlike the previous scenarios, the U-shaped villa demonstrates a greater degree of resistance to changes, as the EUI changes only moderately across the three scenarios. Table 4 shows the comparison between the three iterations.

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Table 4. Comparative summary of annual energy use, EUI, cooling energy share, operational carbon emissions, and thermal comfort across the three iterations of the U-shaped scenario.

Performance Indicator	Iteration 1	Iteration 2	Iteration 3	Change I1 → Best Iteration	% Change
Annual Energy Use (kWh/year)	39,000	38,000	40,000	1000	2.60%
Energy Use Intensity (kWh/m^2·year)	84	82	86	2	2.40%
Cooling Energy Share (%)	43%	42%	41%	1 point	−2.30%
Operational Carbon Emissions ($kgCO_2$/year)	6361	6189	6611	172	2.70%
Thermal Comfort (% of hours)	99%	99%	99%	0%	No change

3.4. Comparative Analysis Between All Masses

The comparison shows that all scenarios improved through their iteration refinements. However, they differ in three main aspects: daylight distribution, overall energy performance after optimization, and sensitivity to orientation.

In terms of daylight and lighting distribution, as indicated by the simulation-based daylight distribution results, the L-shaped and U-shaped scenarios provided a clearer daylight spread across the plan compared to the compact massing. For example, the compact massing model showed a higher internal dark zone in the deeper interior areas where daylight penetration is limited by the geometry. In contrast, the L-shaped design had a better daylight distribution, reduced these deep interior zones, and provided more direct sunlight exposure. The U-shaped massing also improved the daylight distribution across the plan due to its open courtyard, which allowed daylight to be received directly from multiple sides. Figure 4 shows the daylight distribution across the best-performing iteration for all scenarios.

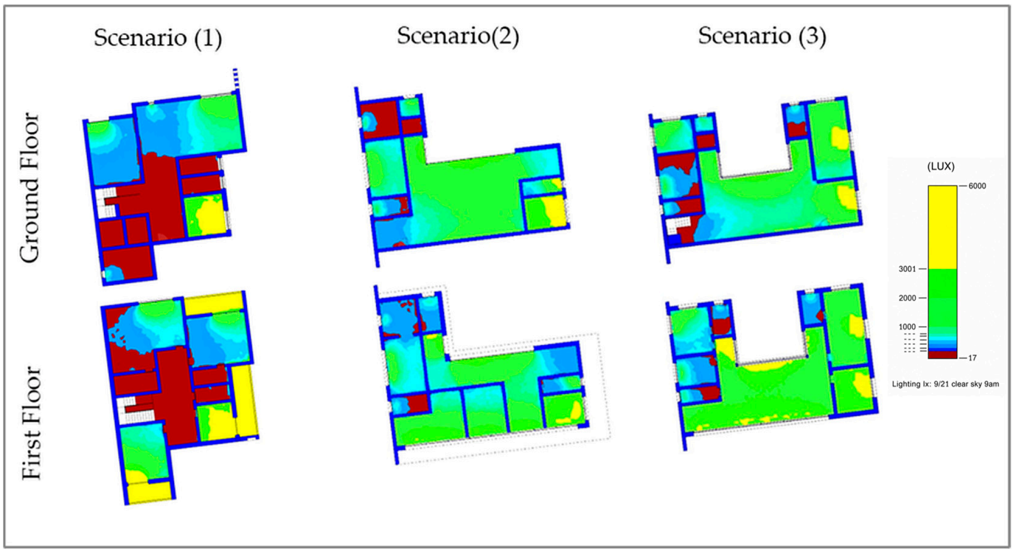

Figure 4. Comparison of daylight analysis results across the refined scenarios.

For the compact scenario, Iteration 3 represents the best-performing configuration. In contrast, for the L-shaped and U-shaped scenarios, Iteration 2 represents the best-performing improved configuration, while Iteration 3 was intentionally developed to evaluate orientation sensitivity rather than further optimization. All scenarios achieved moderate EUI levels after their refinements. However, the L-shape had the lowest EUI, at 79 kWh/m^2. The compact scenario improved to 81 kWh/m^2 (20% from its original base), which is the highest improvement. The U-shaped scenario achieved 82 kWh/m^2 and was the most resilient to refinements due to its stable form. Figures 5 and 6 show the comparison between the EUI and carbon footprint across the best-performing iterations for all scenarios.

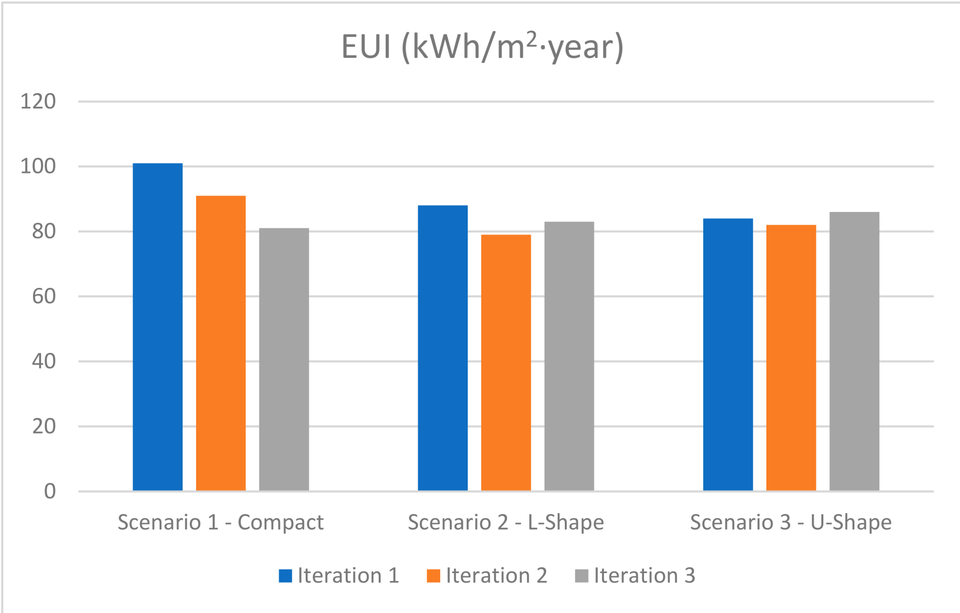

Figure 5. Comparison of EUI results across the best-performing iterations of the three refined massing scenarios.

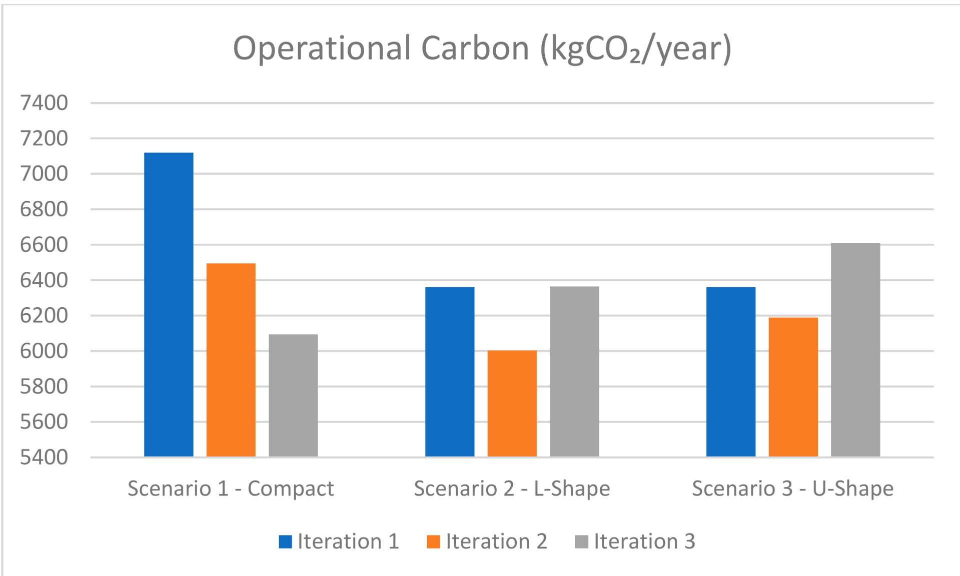

Figure 6. Comparison of operational carbon footprint results across the best-performing iterations of the three refined massing scenarios.

According to the Emirates Green Building Council, an EUI below 90 kWh/m^2·year is considered within the high-efficiency benchmark range in the UAE context. Based on this benchmark, the refined scenarios in this study can be understood as achieving competitive energy performance under hot–arid climate conditions [27].

The impact of the glazing ratios on each design iteration is very clear. In Scenario 1, the window-to-wall ratio (WWR) was reduced significantly from 30.61% in the first iteration to 22.26% in the second iteration, and to 9.29% in the third. In Scenario 2, the reduction was more moderate. It went from 25.10% to 20.56%. Scenario 3 showed a similar pattern as well. It decreased from 23.66% to 21.49%. This shows that each massing type responded differently to façade refinement. In particular, the compact massing needed the largest reduction in glazing to reach its best energy performance, and that is why it showed the greatest improvement in EUI. This finding shows that similar EUI levels were achieved across the different massing types, but with different window-to-wall ratios depending on the shape.

In the second and third scenarios, mirroring the refined L-shaped configuration increased the EUI from 79 to 83 kWh/m^2, while rotating the optimized U-form resulted in an increase in the EUI from 82 to 86 kWh/m^2. This is a clear indication that both form and orientation work together. Figure 7 compares the orientation effect between the two scenarios.

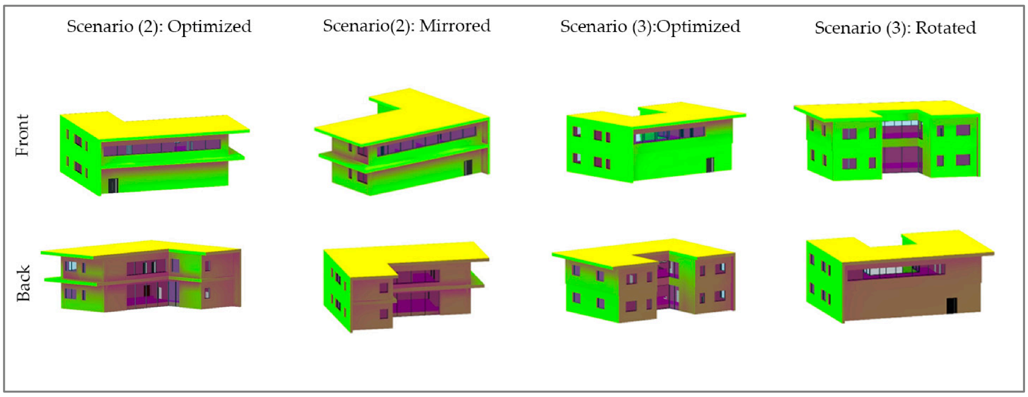

Figure 7. Comparison of orientation effects between the L-shaped and U-shaped scenarios Surface colors represent annual incident solar radiation (kWh/m^2/year), where yellow–green indicates higher solar exposure and purple–brown indicates lower solar exposure.

The increase in EUI observed after mirroring the L-shaped scenario and rotating the U-shaped scenario can be explained by changes in façade solar exposure and the distribution of glazed openings relative to solar orientation. In the improved configurations, the main glazed façades and shaded openings were positioned to reduce direct solar gains during peak afternoon periods. However, after mirroring or rotating the massing, larger glazed surfaces became more exposed to west and southwest solar radiation, which is particularly critical under Abu Dhabi's hot–arid climate conditions. This increased the cooling demand due to higher solar heat gains through the façade openings. In addition, the redistribution of openings altered daylight penetration and internal heat accumulation patterns across the building plan, contributing to the observed increase in EUI values.

Based on the comparison, the results show that the performance of the L-shape massing is better than that of the other massing in terms of daylight distribution and energy consumption. Table 5 shows a comparative analysis of energy performance, iterations, and key design effects across all scenarios.

Table 5. Comparative analysis of energy performance, iterations, and key design effects across all scenarios.

Indicator	Scenario 1	Scenario 2	Scenario 3	Key Observation
Iteration 1 EUI (kWh/m^2·year)	101	88	84	Compact shows highest initial energy demand
Iteration 2 EUI (kWh/m^2·year)	91	79	82	All scenarios improve with glazing reduction + shading

Table 5. *Cont.*

Indicator	Scenario 1	Scenario 2	Scenario 3	Key Observation
Iteration 3 EUI (kWh/m^2·year)	81	83	86	Orientation increases EUI in L and U scenarios
Best EUI (kWh/m^2·year)	81	**79**	82	L-shape achieved the lowest optimized EUI
EUI Reduction (I1 → Best)	≈20%	≈10%	≈2–3%	Compact shows largest improvement potential
Operational Carbon ($kgCO_2$/year)	7119 → 6094	6659 → 6003	6361 → 6189	Carbon follows same pattern as EUI
Cooling Energy Trend (%)	High → reduced	Moderate → reduced	Moderate → slightly reduced	Cooling remains dominant in all scenarios
Daylight Distribution	Deep interior dark zones	Even daylight, fewer dark zones	Good around courtyard, inner zones moderate	L and U improve daylight penetration
Effect of Glazing + Shading	Strong impact	Moderate impact	Limited impact	Effect reduces as form becomes more enclosed
Orientation Impact	Not critical	79 → 83 (+5%)	82 → 86 (+5%)	L and U more sensitive to orientation
Overall Performance Behavior	Highly responsive	Balanced and optimized	Stable but less responsive	Each form reacts differently to same design changes

4. Discussion

This section discusses the study findings, including their interpretation (Section 4.1), the influence of key design parameters on energy performance (Section 4.2), and the practical implementation of BIM-based energy analysis (Section 4.3).

4.1. Interpretation of Findings

The results of this study show that architectural design changes can clearly affect building performance, even when floor area, envelope U-values, and building systems remain fixed. This is consistent with BIM-based energy analysis literature, which explains that energy performance depends strongly on building architecture, interior planning, thermal properties, and orientation/weather data [3,28].

In Scenario 1, less glazing and more shading reduced the cooling load, and that also reduced the carbon footprint. This shows that simple façade changes can make a clear difference in performance.

On the other hand, Scenario 2 (L-shaped massing) showed a different performance behavior. The daylight analysis of the L-shaped scenario showed fewer deep internal zones and more lit spaces than the compact model. All iterations were kept within a moderate EUI range. The refined iteration achieved the best performance at 79 kWh/m^2. However, the mirrored iteration increased the EUI from 79 to 83 kWh/m^2, which confirms that orientation affects façade exposure and cooling demand.

The orientation sensitivity observed in the L-shaped and U-shaped scenarios also highlights the interaction between massing geometry and façade opening distribution. Although glazing reduction and shading improved performance in the improved configurations, changing the orientation altered the exposure of the primary glazed façades to direct solar radiation. In hot–arid climates such as Abu Dhabi, west-facing and southwest-facing façades are particularly sensitive due to high afternoon solar gains, which directly increase indoor heat accumulation and cooling demand. This explains why the mirrored and rotated configurations produced higher EUI values despite maintaining the same material properties and glazing ratios.

Lastly, Scenario 3 (U-shaped massing) showed a relatively stable performance. The refined iteration achieved its best performance at 82 kWh/m^2, but rotating the optimized form increased the EUI from 82 to 86 kWh/m^2. The main energy improvements were mainly due to glazing and shading. However, their effectiveness was influenced by the building's massing and layout.

This study therefore contributes a practical UAE-based example showing that, under fixed floor area, envelope assumptions, and building systems, early architectural decisions alone can still generate measurable differences in EUI, operational carbon, and daylight performance.

4.2. Influence of Key Design Parameters on Energy Performance

The results of this study show that not all design parameters have the same level of impact on energy performance. The glazing ratio and external shading showed the most significant impact on reducing the EUI. In contrast, the massing form influenced the overall performance and how each scenario reacted to changes.

First, glazing ratio had the most direct and measurable impact on energy use. In all scenarios, it was found that increasing the glazing area resulted in an increase in solar heat gain, which in turn increased the cooling demand. This was mainly the case with the compact building scenario. Furthermore, it was found that the glazing ratio and façade iterative refinement resulted in a reduction in EUI from 101 to 81 kWh/m^2 (20%) in the compact scenario. In the L-shaped scenario, it resulted in a reduction in EUI from 88 to 79 kWh/m^2 (10% reduction), and in the U-shaped scenario, a reduction from 84 to 82 kWh/m^2 (2%).

Moreover, the external shading worked together with glazing reduction to improve performance by blocking the direct solar radiation before it entered the building.

Second, massing form influenced how effective these strategies were. For instance, the compact form showed the greatest improvement. The L-shape achieved the best final performance at 79 kWh/m^2, whereas the U-shape showed smaller variation across iterations.

This relationship becomes clearer when the glazing ratios are compared directly. In Scenario 1, the WWR was reduced from 30.61% in Iteration 1 to 9.29% in Iteration 3, and the EUI was reduced from 101 to 81 kWh/m^2. In Scenario 2, the WWR was reduced from 25.10% to 20.56%, and it reached its best EUI at 79 kWh/m^2. In Scenario 3, the WWR was reduced from 23.66% to 21.49%. The EUI improved slightly from 84 to 82 kWh/m^2. This shows that similar energy performance was reached through different levels of glazing reduction and that each massing type responded differently.

4.3. Practical Implementation of BIM-Based Energy Analysis

To support the practical application of BIM-based energy analysis during early conceptual design stages, this section provides guidance for industry professionals by synthesizing lessons learned from design-based research. Such guidance can help address key design-stage barriers, such as a shortage of skilled and experienced personnel, while also providing a framework for applying the same methodology in other contexts.

The proposed workflow enables rapid testing of multiple architectural options within a single BIM environment through the use of appropriate tools. This approach is particularly suitable for the early conceptual design stage, as it facilitates direct comparison of alternatives while supporting informed decision-making. However, it is important to note that the workflow relies on simplified assumptions and should therefore be regarded as a design-support approach rather than a substitute for detailed energy simulation. This limitation is particularly relevant when evaluating peak loads, determining detailed HVAC system sizing, and predicting utility-scale performance. Therefore, the following points highlight key considerations:

- Simulations should be initiated at an early stage to enable the evaluation of massing and façade design decisions before the design is finalized.
- Depending on the building type and local conditions, glazing and shading can significantly influence performance; therefore, architects and designers should prioritize these elements early in the design process.
- At the conceptual stage, BIM tools should primarily be used for comparative analysis rather than for producing precise final energy estimates. They are effective in indicating relative performance between design options; however, more detailed energy simulation tools should be integrated as the design process progresses.
- Energy analysis should be conducted iteratively throughout the design process rather than as a one-time exercise. This involves testing the design, implementing modifications, and re-evaluating performance until improved outcomes are achieved.

5. Conclusions

The study demonstrates that the performance of villas in a hot–arid climate is influenced by building form, internal spatial arrangements, and orientation. It also shows that design decisions made by architects at the conceptual design stage can significantly reduce energy consumption and carbon emissions. Moreover, the results highlight the importance of early-stage design decisions, as modifications to building form, orientation, and façade configuration were found to substantially influence long-term energy performance and sustainability outcomes.

However, the topic requires further exploration to address remaining gaps and uncover new research areas. One potential avenue is to expand the scope of the study by investigating additional massing typologies and variations. In the present study, emphasis is placed on three primary building forms: compact, L-shaped, and U-shaped. Future research could examine other typologies, such as bar-shaped forms, fully enclosed courtyards, or split masses, in order to better understand how different geometric approaches perform in hot–arid climates.

The contribution of this study is not limited to confirming the usefulness of BIM-based energy analysis, which has already been widely discussed in the literature, but rather to demonstrating a structured comparative workflow tailored to residential villas in a UAE hot–arid climate context. The study integrates massing comparison, façade refinement, daylight interpretation, operational carbon assessment, and orientation testing within a unified early-stage BIM workflow using industry-accessible tools.

For professional practice, these findings suggest that BIM-based energy analysis is most effective when applied early in the design process as a comparative and iterative decision-support method, rather than as a substitute for detailed final engineering simulations.

Finally, as this study focuses on the use of BIM for energy performance analysis and comparative evaluation during the conceptual and early design stages, future research should investigate the following directions:

- The extension of the proposed approach to later design phases, where multi-stakeholder coordination becomes increasingly critical for ensuring efficient construction processes. Particular emphasis should be placed on mechanisms that enable effective stakeholder collaboration.
- The examination of relevant business models that can support broader adoption of the proposed approach, as well as strategies for enhancing knowledge dissemination and facilitating the practical implementation of BIM within industry practice.

- The integration of circular economy principles and life-cycle assessment within the design and delivery workflow, to ensure the efficient use of materials and resources.

Author Contributions: Conceptualization, F.A.; methodology, F.A.; software, F.A.; validation, F.A., and A.S.; formal analysis, F.A., and A.S.; investigation, A.S.; resources, F.A., and H.H.; writing—original draft preparation, F.A.; writing—review and editing, H.H., A.S., and A.A.R.; visualization, F.A.; supervision, A.S., and A.A.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the American University of Ras Al Khaimah, Office of Research and Sustainability, grant number [ENGR/008/24].

Data Availability Statement: The data supporting the findings of this study are available from the authors upon reasonable request. The BIM/Revit models are not shared. Selected simulation outputs and summary results can be provided upon request.

Acknowledgments: The authors acknowledge the use of Autodesk Revit 2026 under an educational student license and Enscape Impact under a student discounted license for the development and simulation of the BIM models used in this study. During the preparation of this manuscript, the authors used ChatGPT 5.5 (OpenAI) for general guidance on manuscript structure and support in organizing summary tables. The authors reviewed and edited all output and take full responsibility for the content of this publication.

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

Abbreviations

The following abbreviations are used in this manuscript:

AEC	Architecture, Engineering, and Construction
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BIM	Building Information Modeling
CO_2	Carbon Dioxide
EUI	Energy Use Intensity
HVAC	Heating, Ventilation, and Air Conditioning
PBRS	Pearl Building Rating System
UAE	United Arab Emirates
WWR	Window-to-Wall Ratio

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