



A Novel Vernacular–Modern Hybrid Building Design for Sustainable Thermal and Environmental Performance

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Article Info

Received 27 December 2025
Accepted 08 January 2026
Available online 31 May 2026

Keywords:

Environmental Performance;
Hybrid building design;
Vernacular architecture;
Energy efficiency;
Bioclimatic design;
Sustainable Development.

Abstract:

The construction sector is a major contributor to global energy consumption and carbon emissions, particularly in regions with extreme climatic conditions. Traditional Iranian architecture offers valuable passive design strategies, yet its structural limitations restrict widespread use in contemporary practice. This study develops and evaluates a hybrid building model that integrates vernacular bioclimatic principles with modern structural systems to enhance thermal performance, energy efficiency, and cultural compatibility in semi-arid climates. Four building typologies—a traditional adobe building with a thatched coating, a traditional adobe building without a coating, a modern reinforced-concrete building, and a proposed hybrid model—were analyzed using dynamic energy simulations in DesignBuilder and structural modeling in ETABS and SAFE. Results show that the traditional thatch-coated building achieved the lowest cooling load, the most stable comfort temperatures, and the lowest maximum daily operating temperatures, due to its high thermal mass and natural insulation. The modern building exhibited the poorest thermal performance, driven by low-mass walls and high heat transfer. The hybrid building demonstrated a balanced profile: its thermal performance closely matched that of traditional structures while ensuring structural resilience and compliance with modern seismic standards. These findings highlight the potential of hybrid construction as a scalable, environmentally responsive solution that merges indigenous architectural wisdom with contemporary engineering needs. The proposed framework can guide future sustainable housing strategies in Iran and other regions with similar climatic and cultural contexts.

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Supplementary information: Supplementary information for this article is available at <https://cste.journals.umz.ac.ir/>

Please cite this paper as: Shams, A. , Khane, A. , Biglarijoo, N. , Mousavi, S. , Karami, H. , & Bagheri, M. (2026). A Novel Vernacular–Modern Hybrid Building Design for Sustainable Thermal and Environmental Performance. Contributions of Science and Technology for Engineering, 3(2), 39-50. doi:10.22080/cste.2026.30721.1101.

1. Introduction

Rapid population growth and rising energy demands have intensified global environmental problems, reducing greenhouse gas emissions a top priority [1]. In both developed and developing countries, researchers are actively exploring ways to reduce energy use and develop sustainable environmental strategies to lower carbon emissions and enhance human well-being [2]. The construction sector, responsible for over 35% of global greenhouse gas emissions, plays a key role in this challenge due to the significant energy use in material extraction, manufacturing, transportation, and building operations [3,

4]. Consequently, the sustainability and energy efficiency of modern architecture are increasingly examined by environmental scientists worldwide.

A significant portion of emissions stems from the need to create buildings that are structurally safe and thermally comfortable, especially when high-conductivity materials increase heating and cooling demands [3]. In this context, climate change has heightened the urgency of adopting construction strategies that enhance passive performance while reducing reliance on non-renewable energy sources. These pressures have sparked renewed interest in traditional architectural methods, which have evolved over centuries



through experimentation and deep knowledge of local climates [5]. Among these, Iranian vernacular architecture is notable for its long history, cultural richness, and effective adaptation to the environment.

Traditional Iranian buildings use thick walls, clay bricks, thatch mortar, basements, courtyards, and windcatchers—design elements that work together to control indoor temperatures while maintaining cultural identity [6, 7]. These structures rely heavily on locally sourced materials, resulting in lower embodied energy and less environmental impact [8]. However, despite their thermal benefits, vernacular buildings often lack sufficient resistance to earthquakes, strong winds, and other natural hazards [9]. On the other hand, modern buildings benefit from reinforced materials and structural reliability but usually have poor passive thermal performance due to thin, low-thermal-mass walls and highly conductive materials. These contrasting strengths and weaknesses highlight the need for an approach that can combine the benefits of both systems.

This study aims to develop and thoroughly evaluate a hybrid building model that blends the bioclimatic principles and indigenous materials of Iranian vernacular architecture with modern structural reinforcement systems. The goals are to improve thermal comfort, lower operational energy use, increase resistance to natural hazards, and support cultural preservation. Specifically, this research examines how building envelope features—including wall thickness, insulation, and glazing type—impact thermal performance in semi-arid climates. It explores strategies to reduce dependence on non-renewable energy sources through passive design. The study also examines how hybrid configurations can help preserve regional architectural heritage while addressing current structural and environmental challenges.

Although many studies have examined traditional and modern buildings separately in Iran, the literature lacks simulation-based evaluations of hybrid models that simultaneously address passive thermal performance, structural safety, and cultural compatibility. This study fills that gap by using computational simulations (DesignBuilder for thermal analysis and ETABS/SAFE for structural validation) to compare traditional, modern, and hybrid building prototypes quantitatively. The study shows how vernacular bioclimatic principles can be effectively integrated with modern structural systems to improve energy efficiency and sustainability in Iran's semi-arid regions.

2. Climatic and Architectural Context of Traditional Iranian Buildings

2.1. Vernacular Architectural Features in Iran

Traditional Iranian cities exhibit a rich architectural heritage shaped by centuries of adaptation to environmental, social, and cultural conditions [10, 11]. Vernacular houses typically include separate rooms for summer and winter use, each designed to respond to seasonal climatic needs. Winter rooms are designed with short walls, small windows, and a fireplace to retain heat. In contrast, summer rooms are

strategically positioned between the inner and outer courtyards to maximize shading and avoid direct sunlight. This arrangement reflects a deep understanding of solar geometry and airflow patterns.

These design principles are exemplified in the historic residence of Brigadier General Sedehi in Khomeini Shahr, Isfahan Province (Figure 1). Traditional houses commonly feature wooden doors and windows with colored glass, which filter sunlight, reduce heat gain, and create visually calming interior environments. Beyond their aesthetic and psychological benefits, the colors were traditionally believed to deter insects and animals from entering the living spaces. Summer rooms often incorporate tall, thick walls and full-length windows that promote natural ventilation, creating cooler interior conditions without mechanical systems [12].



Figure 1. Historic house of Brigadier General Sedehi, Khomeini Shahr, Isfahan Province

The geometry, orientation, and materiality of these structures—characterized by high thermal mass and low thermal conductivity—enable them to maintain stable indoor temperatures despite extreme diurnal temperature fluctuations. However, despite their environmental benefits, vernacular buildings face structural limitations caused by their reliance on load-bearing adobe walls, which lack adequate resistance to earthquakes, wind forces, and other natural hazards. These constraints offer opportunities to integrate modern structural systems while preserving traditional climatic design principles.

2.2. Geographical and Climatic Conditions of Isfahan

Isfahan Province, located in the central Iranian Plateau (30°42'–34°30' N; 49°36'–55°30' E), covers an area of approximately 107,029 km² and is the second-largest province in the country. Its geography, positioned between the Zagros Mountains and the arid central plains, generates a predominantly semi-arid to arid climate characterized by hot summers, cold winters, large diurnal temperature ranges, and low humidity. These climatic features have played a decisive role in shaping local building traditions.

As shown in Figure 2, the province's central location and exposure to desert climatic patterns have historically influenced construction methods, spatial configuration, and

material selection. Vernacular architecture in Isfahan responds to these conditions through strategies such as inward-facing courtyards, thick masonry walls, shaded transitional spaces, and the use of high-thermal-mass

materials that delay heat transfer. These architectural adaptations align closely with passive design principles, enabling residents to achieve indoor thermal comfort with minimal energy consumption.

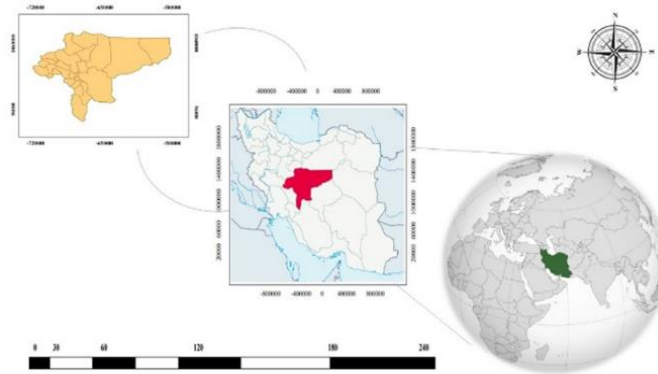


Figure 2. Geographical location of Isfahan Province

This strong relationship between climate and traditional building practice underscores the relevance of examining vernacular strategies as potential foundations for developing hybrid buildings that meet modern structural and environmental demands.

3. Building Materials, Construction Techniques, and Their Thermal Implications

3.1. Importance of Material Selection in Thermal Performance

Material selection plays a fundamental role in determining a building’s thermal behavior, particularly in climates with large temperature fluctuations such as those found in central Iran. Wall thickness, thermal mass, and thermal resistance directly affect heat absorption in summer and heat loss in winter. In traditional architecture, thick masonry walls provided both structural stability and improved thermal inertia, helping maintain a stable indoor environment with minimal mechanical intervention. By contrast, modern construction—characterized by lightweight walls and lower thermal mass—often results in higher heating and cooling demands despite its structural advantages.

Two key parameters govern thermal performance: heat capacity (thermal mass) and thermal resistance (R-value). Increasing either parameter reduces internal surface temperature fluctuations and delays the transmission of outdoor temperature changes into indoor spaces. This delay is particularly valuable in Isfahan’s semi-arid climate, where daily temperature swings are significant. Given Iran’s rate of temperature increase—roughly twice the global average—optimizing building materials to minimize heat exchange is essential for reducing electricity consumption and enhancing environmental sustainability [13].

3.2. Traditional Iranian Building Materials and Systems

Traditional Iranian buildings rely heavily on locally sourced materials, including adobe, brick, lime, plaster, stone, wood, soil, sand, and natural mortars. These materials

were chosen not only for availability but also for their climatic compatibility and low embodied energy [13]. Adobe bricks bonded with straw mortar form the primary structural system in many regions, particularly in hot and dry areas. Roofs typically consist of timber elements covered with brickwork and coated with a protective layer of thatch mortar, which acts as an effective insulator against moisture and heat.

Straw mortar—applied at a thickness of 2–3 cm—provides natural thermal insulation and moisture resistance. When adequately prepared, it can remain durable for years, though it is vulnerable to erosion from rain and wind. To enhance stability, straw fibers are added to prevent cracking during drying. Variations in mortar composition emerge across landscapes: mountainous regions use clay mixed with sand and gravel, while some areas incorporate clay, straw, and salt to create water-resistant coatings used in traditional bathhouse domes. Floors commonly use square clay bricks (25×25×4.5 cm), contributing additional thermal mass and durability. While traditional materials excel in thermal performance and environmental compatibility, their structural limitations—remarkably low resistance to earthquakes and strong winds—pose significant risks in modern contexts.

3.3. Modern Iranian Construction Materials and Systems

Modern construction in Iran and worldwide predominantly utilizes reinforced concrete or steel frames combined with lightweight infill walls. These systems provide superior resistance to earthquakes, winds, and other natural hazards. Roofs are often constructed with block-joint systems made from cement, clay, or polystyrene blocks, while floor finishes typically include ceramic tiles or wooden parquet [14].

Despite their structural advantages, modern construction materials come with notable drawbacks. The production of cement, steel, and manufactured insulation materials is energy-intensive and contributes significantly to carbon emissions [10]. Additionally, lightweight walls with low

thermal mass facilitate rapid heat transfer between indoor and outdoor environments, thereby increasing energy consumption for cooling and heating. These issues, combined with the aesthetic disconnect between modern buildings and the cultural identity of many Iranian cities, have prompted growing interest in alternative approaches [15].

Constraints imposed by heritage protection policies further complicate the modernization of traditional structures. Retrofitting historical vernacular buildings is often restricted to prevent cultural damage [14]. As a result, combining modern structural systems with vernacular

architectural elements offers a promising approach to addressing both cultural and environmental needs.

3.4. Comparative Analysis of Traditional and Modern Techniques

A structured comparison between traditional Iranian construction and contemporary methods highlights fundamental differences in durability, environmental impact, material sourcing, structural performance, and maintenance requirements. Table 1 summarizes these distinctions.

Table 1. Comparison of fabrication techniques in traditional and modern buildings

Subject	Modern Construction Techniques	Traditional Iranian Building Techniques
Structural system	Reinforced concrete or steel frame	35 cm thick load-bearing brick/adobe walls
Wall type	Cement block or clay brick	Clay brick/adobe brick
Roof material	Block-joist system (cement, clay, or polystyrene blocks)	Brick vaults or wooden logs with 2 cm wooden planks
Floor material	Ceramic tiles or wooden parquet	25×25 cm adobe/clay bricks
Exterior finish	Stone, wood, composite panels, or cement render	Clay bricks, glazed bricks, or thatch mortar coating
Roof covering	Isogam or nano-insulation coatings	Thatch mortar (mud + straw coating produced locally)
Mortar type	Cement-sand mortar	Mud, plaster, lime, Saroj, or bitumen mortars

This comparison underscores a central challenge: traditional buildings excel in thermal behavior but lack structural resilience, while modern buildings provide structural safety but underperform thermally and environmentally [16]. These contrasting characteristics create a strong rationale for pursuing a hybrid construction approach.

3.5. Integrating Hybrid Design Approaches for Safety and Sustainability

Building upon the strengths of both systems, this research introduces a hybrid architectural model that merges vernacular design principles with modern structural reinforcement [17]. The prototype—a 145 m² residential unit built in Isfahan (Figure 3)—includes key spatial elements, such as an inner courtyard, living room, dining area, bedrooms, kitchen, and transitional outdoor spaces, all reflecting the organization of traditional Iranian homes.

The hybrid building achieves environmental and structural goals through several strategies:

- Reinforced concrete frames provide seismic and wind resistance.
- Thick brick walls (35 cm) enhance thermal mass, closely resembling traditional construction.
- Locally manufactured bricks reduce transportation emissions and support regional economies.
- Wooden doors and windows, combined with double-glazed glass filled with 90% argon gas, reduce heat loss and integrate traditional aesthetics with modern energy performance.
- Courtyard microclimate: the central courtyard and small water pool help naturally regulate indoor temperatures through evaporative cooling and shading.
- Thatch mortar and clay-based finishes retain cultural identity while offering climate-responsive performance.



Figure 3. A hybrid house constructed in Isfahan province

Figure 4 illustrates the daylight absorption pattern, where blue/green areas represent lower illumination, yellow/orange moderate levels, and red areas the highest

intensities. This analysis supports optimizing natural lighting while preventing overheating.

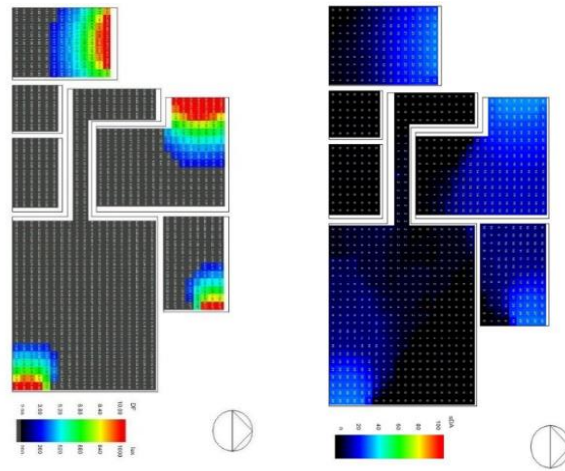


Figure 4. The amount of light absorbed throughout the day

This hybrid design represents a practical synthesis of traditional environmental wisdom and contemporary engineering, forming the conceptual foundation for the simulation-based analysis presented in the following sections.

4. Methodology

This study employs a comparative simulation-based approach to evaluate the thermal performance, structural resilience, and environmental implications of four distinct building typologies representative of traditional, modern, and hybrid construction in central Iran. The methodological framework integrates architectural modeling, structural analysis, and dynamic energy simulation to ensure a comprehensive assessment under consistent climatic and operational conditions [18, 19].

4.1. Overview of Building Typologies

Four building types were selected based on their relevance to architectural practice in semi-arid regions of Iran:

- 1) Traditional Adobe Building with Thatch Coating (A)
 - 35 cm adobe walls
 - Wood-framed doors/windows with 3 mm single glazing
 - thatch mortar on exterior walls and roof
 - Clay brick flooring (25 × 25 cm)
- 2) Traditional Adobe Building without Thatch Coating (B)

- 35 cm adobe walls
- Wood-framed doors/windows with 3 mm single glazing
- Cement–sand mortar exterior finish
- Clay brick flooring (25 × 25 cm)

3) Modern Building (C)

- Reinforced concrete frame
- 10 cm hollow clay-block walls
- PVC windows with 6 mm double-glazed argon-filled units
- Unlit beam roof with Isogam insulation
- Ceramic flooring

4) Hybrid Building (D)

- Reinforced concrete frame combined with 35 cm brick walls
- Wooden window frames and 6 mm double-glazed argon-filled glass
- Unlit beam roof with Isogam insulation
- Local clay bricks (25 × 25 cm) for flooring
- Inner courtyard and passive cooling features inspired by vernacular design

All four models were designed with consistent geometry, opening sizes, internal zoning, and building height to ensure comparability. Table 2 summarizes the specifications.

Table 2. Comparison of fabrication techniques in traditional and modern buildings

Building Type	Specifications
Traditional Adobe Building with Thatch Coating (A)	<ul style="list-style-type: none"> • 35 cm adobe walls • Wooden door and window frames with 3 mm single glazing • Straw-mortar exterior coating on walls and roof • 25×25 cm square adobe bricks used as floor and courtyard covering
Traditional Adobe Building without Thatch Coating (B)	<ul style="list-style-type: none"> • 35 cm clay-brick walls • Wooden door and window frames with 3 mm single glazing

	<ul style="list-style-type: none"> • Cement–sand mortar used as exterior finish • 25×25 cm square clay bricks used as floor and courtyard covering
Modern Building (C)	<ul style="list-style-type: none"> • Reinforced concrete frame • 10 cm hollow clay-block walls • Metal door frames and PVC windows • 6 mm double glazing filled with 90% argon gas • Unlit beam roof with Isogam insulation • Microcement exterior façade • Ceramic flooring used throughout
Hybrid Building (D)	<ul style="list-style-type: none"> • Reinforced concrete frame • 35 cm Kazakh brick* walls • Wooden doors and wooden-framed double-glazed windows (6 mm glass, 90% argon-filled) • Unlit beam roof with Isogam insulation • 25×25 cm square clay bricks proposed for floor and courtyard surfaces

*Kazakh brick is a locally manufactured fired-clay brick commonly used in Iran for both load-bearing and infill walls. These bricks are characterized by relatively high density, moderate thermal conductivity, and substantial thermal mass.

4.2. Structural Modeling and Analysis

To ensure structural adequacy—especially for the hybrid building—structural simulations were performed using:

- ETABS for 3D structural analysis
- SAFE for foundation and slab performance evaluation

These tools evaluated the structural behavior of the hybrid building under seismic and wind loads typical of the region.

The reinforced concrete frame was modeled in accordance with contemporary Iranian seismic codes, ensuring safety while integrating vernacular architectural features [20-24].

Figure 5 illustrates a detailed view of the concrete structural design modeled in ETABS and shows the building's architectural model.

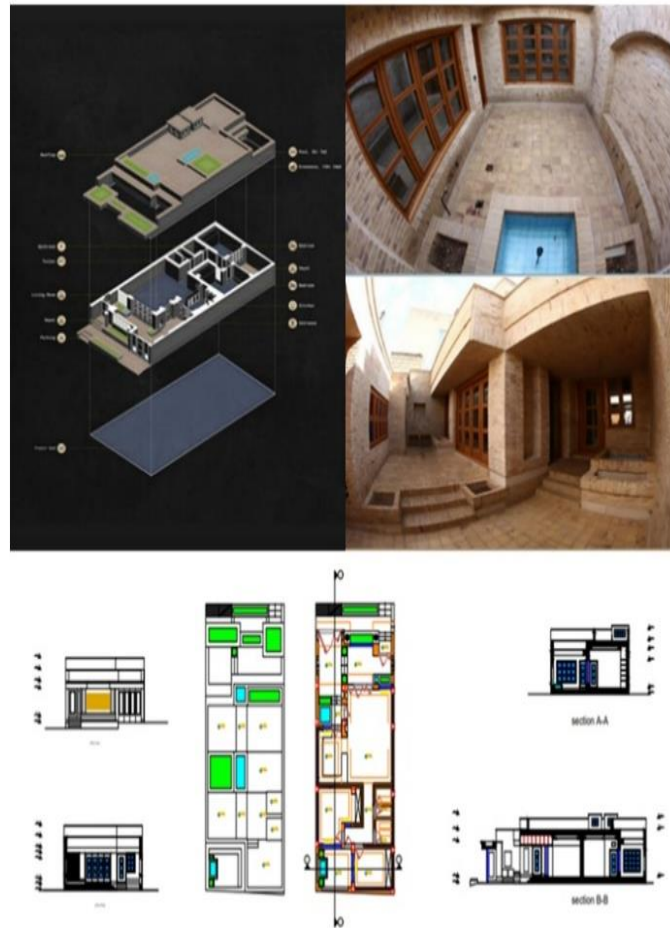


Figure 5. A view of a concrete building design with ETABS software and a 3D architectural model

4.3. Energy Simulation Using DesignBuilder

Thermal performance simulations were performed using DesignBuilder (v. 6.1.0.006). Figure 6 illustrates a modeled configuration. Each building model was subjected to identical operational and environmental settings:

- Climate: Semi-arid climate of Isfahan Province
- Occupancy: Family of four (16:00–08:00 daily presence)
- Internal loads:

- Equipment: 1200 kJ/h
- Occupants: 800 kJ/h
- Lighting: 300 kJ/h
- Ventilation: Natural ventilation patterns consistent across all models
- Boundary conditions: Same schedules, infiltration rates, and usage patterns

Outputs extracted from simulations included:

- Total cooling load (kWh)
- Indoor comfort temperature (°C)
- Maximum daily operating temperature (°C)
- Heat transfer characteristics



Figure 6. An example of the modeled configuration.

4.4. Evaluation Criteria

The comparative evaluation focused on five principal indicators relevant to thermal behavior and passive performance:

- 1) Total Cooling Load, energy required to bring indoor temperatures to acceptable comfort levels.
- 2) Comfort Temperature, the degree to which each building maintains temperatures within the passive comfort range (typically 22–26°C) [25].
- 3) Maximum Daily Operating Temperature, the highest indoor temperature reached without mechanical cooling, indicating passive resilience.
- 4) Heat Transfer and Envelope Performance, evaluated through wall assemblies, glazing types, and roof insulation.
- 5) Building Mass and Thermal Inertia, derived from material density and wall thickness, influence thermal inertia.

These indicators enable systematic comparison of vernacular, modern, and hybrid strategies under identical climatic conditions.

4.5. Stepwise Research Methodology

The overall workflow of the study—from the identification of the research problem to the derivation of conclusions—is illustrated in Figure 7. This stepwise framework provides

a structured, systematic representation of the methodological process used in this research.

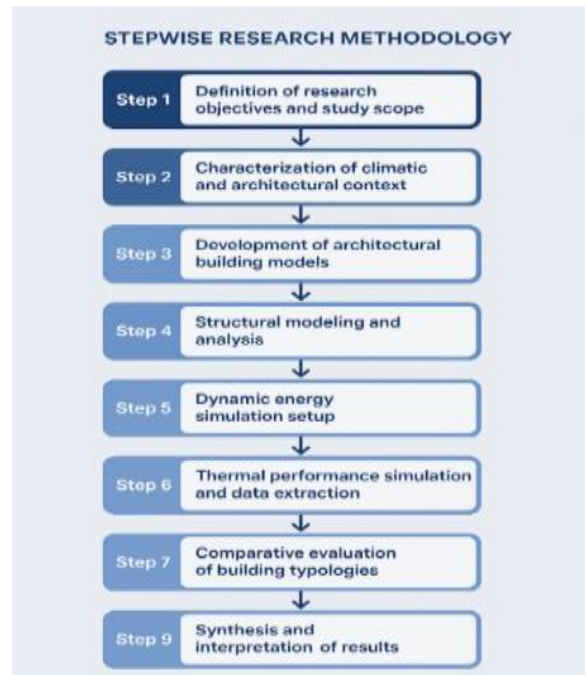


Figure 7. Stepwise research methodology of the study

4.6. Research Design Logic

This integrated methodological framework allows:

- Controlled comparison under standardized geometry and usage patterns
- Isolation of material and system effects on thermal behavior
- Evaluation of hybrid designs as a bridge between tradition and contemporary engineering
- Context-appropriate recommendations for sustainable housing in Iran

This methodology establishes a robust basis for the comparative results presented in Section 5.

5. Results and Discussion

This section presents a comparative analysis of four building types—traditional adobe buildings with and without thatch coating (A and B), a modern building (C), and a hybrid building (D)—modeled in DesignBuilder under identical climatic, geometric, and operational conditions. The evaluation focuses on building mass, total cooling load, comfort temperature, and maximum daily operating temperature. Together, these parameters provide a comprehensive assessment of thermal performance and passive resilience in Isfahan’s semi-arid climate.

5.1. Building Mass Comparison

Figure 8 illustrates the total mass of each building. As expected, the traditional building with thatched coating (A) has the most significant mass due to its thick adobe walls and dense natural materials, followed by the traditional

building without thatch (B) and the hybrid building (D). The modern building (C), constructed with lightweight hollow clay blocks and thin walls, has the lowest mass.

Higher building mass generally corresponds to higher thermal inertia, enabling indoor temperatures to remain

more stable throughout the day. This relationship helps explain subsequent findings regarding cooling load and comfort performance, as mass affects the building's ability to delay and dampen external temperature fluctuations.

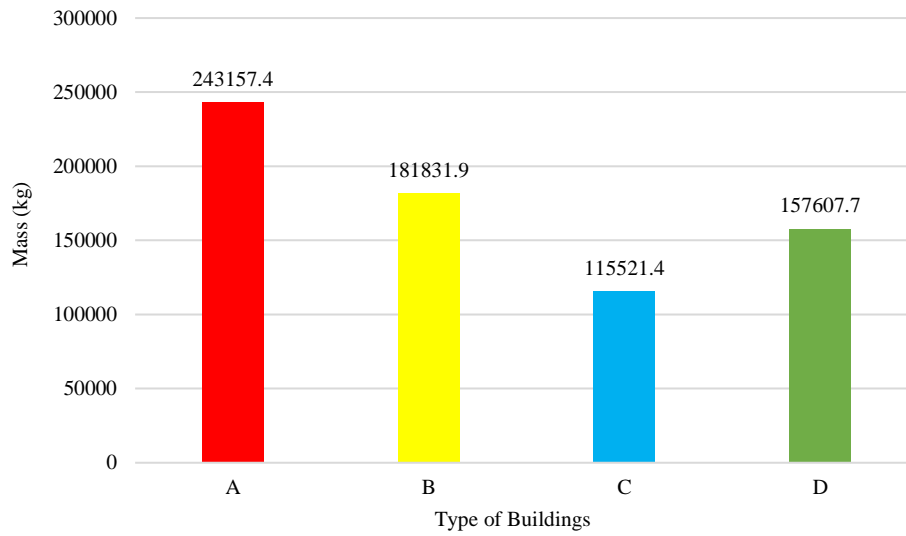


Figure 8. Comparison of the mass of the studied buildings

5.2. Total Cooling Load

The total cooling load quantifies the energy required to maintain comfortable indoor conditions. As shown in Figure 9, the traditional building with thatch coating (A) exhibits the lowest cooling load among all models. This superior performance is primarily attributed to:

- High thermal mass of adobe
- Natural insulation provided by the thatch coating
- Reduced heat transfer through thick walls

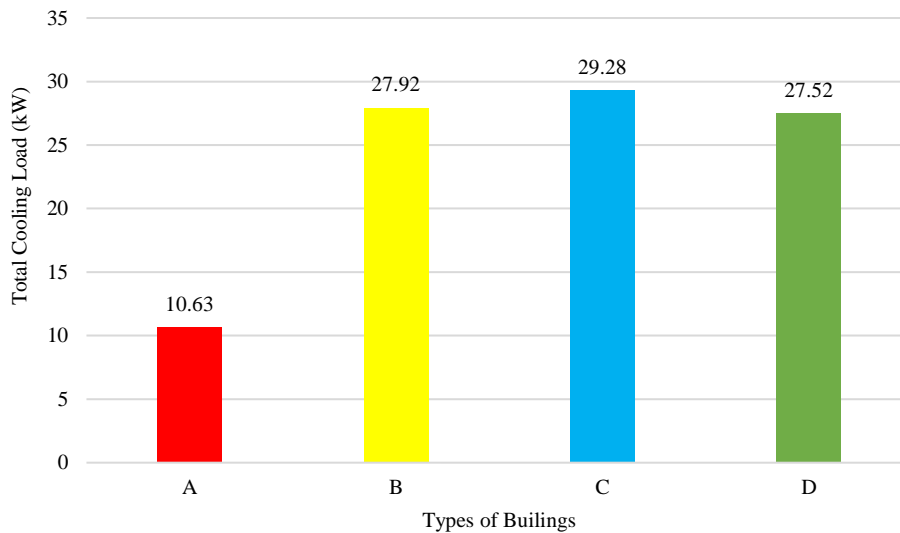


Figure 9. Comparison of total cooling loads in the studied buildings

By contrast, the modern building (C) has the highest cooling load due to its low thermal mass and high heat transfer rate. The hybrid building (D) performs substantially better than the modern building. It closely approaches the performance of the traditional uncoated adobe building (B),

demonstrating the benefits of combining high-mass brick walls with modern glazing.

The difference between buildings A and B further highlights the significant role of thatch mortar in reducing heat gain. This coating provides an additional insulating

layer that reduces conductive and radiative heat transfer, especially during hot daytime hours [26, 27].

Compared to the modern building (C), the hybrid building (D) demonstrates a substantial reduction in cooling demand. Simulation results indicate that the hybrid model reduces total cooling load by approximately 25–30%, depending on daily operating conditions. Although it does not fully match the performance of the traditional thatch-coated building (A), its cooling load remains within 10–15% of the traditional uncoated adobe model (B). These quantified improvements highlight the effectiveness of combining high-thermal-mass walls with improved glazing and vernacular spatial strategies in reducing operational energy demand.

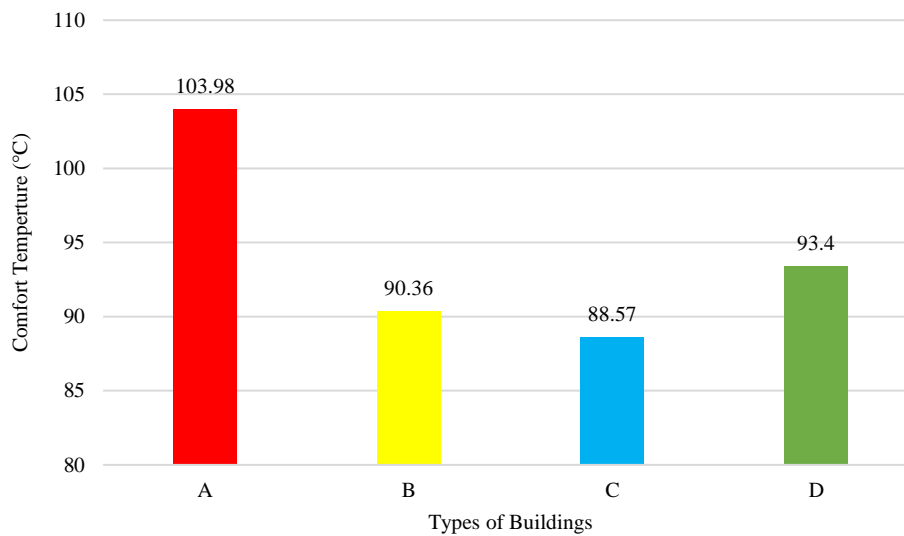


Figure 10. Comparison of comfort temperature (°C) in the studied buildings

The modern building (C) exhibits the least favorable performance, with significant indoor temperature fluctuations due to rapid heat transfer through its thin walls. The hybrid building (D), equipped with 35 cm brick walls and double-glazed argon-filled windows, demonstrates a notable improvement over both modern and uncoated traditional structures. This confirms that high-performance glazing and thermally massive walls can compensate for the absence of traditional coatings.

5.4. Maximum Daily Operating Temperature

Maximum daily operating temperature reflects the highest indoor temperature reached during the day without cooling systems. This metric is crucial in hot climates, where the effectiveness of passive cooling strategies determines occupant comfort and energy demand [31, 32].

Figure 11 indicates that the thatch-coated traditional building (A) achieves the lowest maximum daily temperature. The insulating properties of the thatch coating significantly reduce peak heat transfer, enabling the building to remain cooler during the hottest hours. This finding aligns with prior research that emphasizes the value

5.3. Comfort Temperature Analysis

Comfort temperature represents the indoor temperature achieved without mechanical cooling and is a key indicator of passive performance. Buildings that maintain indoor temperatures within or near the typical comfort range (22–26°C) are more effective in reducing dependence on active cooling systems [28–30].

As shown in Figure 10, the traditional thatch-coated building (A) achieves the most favorable comfort temperatures. Its thick adobe walls, combined with the insulating exterior layer, maintain more stable interior conditions even during peak ambient temperatures. Recent studies identify comfort temperature as a core indicator of passive design success, emphasizing the importance of materials that minimize deviation from comfort thresholds.

of high thermal inertia and natural insulation in passive design.

In contrast, the modern building (C) reaches the highest maximum temperatures because of its lightweight walls with low heat storage capacity. The hybrid building (D) again falls between the traditional and modern buildings, confirming the effectiveness of its combined strategies—thick brick walls, improved glazing systems, and vernacular spatial configuration.

5.5. Influence of Glazing on Heat Transfer

The disparity between buildings B (traditional without thatch) and D (hybrid) underscores the critical role of glazing in thermal performance. Although both structures feature walls of identical thickness (35 cm), their thermal behaviors differ significantly due to the type of window systems used:

- Building B: 3 mm single glazing → high U-value → significant heat loss and heat gain
- Building D: 6 mm double glazing with 90% argon gas → lower U-value → reduced heat transfer

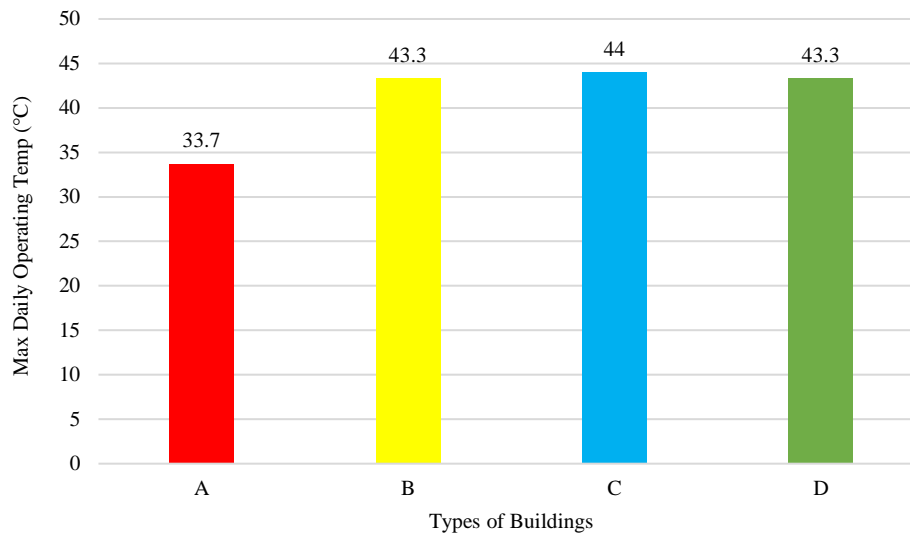


Figure 11. Comparison of maximum daily operating temperatures (°C)

This demonstrates that upgrading glazing technology can dramatically enhance energy efficiency even in buildings with traditional materials. The hybrid model's improved performance validates the use of modern glazing technologies alongside vernacular wall systems [33-35].

5.6. Summary of Construction Techniques and Performance

Table 3 summarizes the key characteristics of each building category, including material sourcing, structural performance, energy consumption, environmental impact, cultural compatibility, and maintenance requirements. The results show:

- Traditional buildings (A and B) are environmentally friendly, culturally compatible, and thermally efficient but structurally weak.
- Modern buildings (C) are structurally strong but have the poorest thermal performance and higher environmental impacts.
- Hybrid buildings (D) strike a balance—structurally resilient, thermally efficient, culturally consistent, and environmentally moderate.

These findings highlight that hybrid construction represents a viable path forward, combining the strengths of traditional and modern methods to achieve sustainable, resilient building performance in semi-arid climates.

While the primary focus of this study is operational thermal performance, embodied carbon represents an essential complementary dimension of environmental sustainability. Traditional Iranian buildings typically rely on locally sourced, minimally processed materials such as adobe, clay brick, wood, and straw mortar, which generally have lower embodied carbon than industrial materials like reinforced concrete, steel, and synthetic insulation. Despite their structural advantages, modern construction systems are associated with higher embodied emissions due to energy-intensive material production and transportation.

The proposed hybrid building occupies an intermediate position. Although it incorporates reinforced concrete elements, the extensive use of thick clay-brick walls and locally manufactured materials helps reduce overall embodied carbon relative to thoroughly modern buildings. A comprehensive life-cycle assessment was beyond the scope of this study; however, future research should quantify embodied emissions alongside operational energy to provide a more holistic evaluation of environmental performance.

From a practical perspective, the hybrid construction approach represents a feasible compromise between traditional and modern building systems. While initial construction costs may be higher than those of purely vernacular buildings due to the inclusion of reinforced-concrete structural elements and double-glazed windows, they remain generally lower than those of thoroughly modern buildings that rely extensively on industrial materials and finishes. Moreover, reduced cooling energy demand, reliance on local labor and materials, and improved durability suggest that hybrid buildings may offer favorable long-term economic performance, particularly in regions with high cooling loads.

5.7. Limitations of the Study

This study is subject to several limitations. First, the analysis is based on simulation models that assume standardized material properties, occupancy schedules, and user behavior, which may differ from real-world conditions. Second, climatic data were based on typical meteorological year inputs and do not capture long-term climate variability or future climate change scenarios. Third, the study focused primarily on operational thermal performance and did not include a complete life-cycle assessment or detailed cost analysis. Finally, structural validation was limited to code-compliant modeling rather than experimental testing. Despite these limitations, the comparative framework provides robust insights into the relative performance of

traditional, modern, and hybrid building strategies under consistent conditions.

Table 3. Comparison of construction techniques and energy performance among the four studied buildings.

Item	Traditional + Thatch (A)	Traditional – Thatch (B)	Modern (C)	Hybrid (D)
Material sourcing	All materials local	All materials local	Mostly non-local	Mostly local
Structural strength	Low; weak against rain/wind	Low; weak against earthquakes	High; strong under all hazards	High; strong under all hazards
Exterior finish	Thatch mortar	Brickwork pattern	Microcement	Brickwork pattern
Interior finish	Plastered walls	Plastered walls	Plastered walls	Plastered walls
Roof system	Timber + straw-mortar	Timber + straw-mortar	Block-joist + Isogam	Block-joist + Isogam
Thermal behavior	Very low heat transfer; excellent thermal mass	Low heat transfer	High heat transfer	Low heat transfer; improved glazing
Energy consumption	Lowest	Low	Highest	Low (near traditional)
Environmental impact	Very low	Very low	High	Moderate-low
Cultural compatibility	High	High	Low	High
Workforce	Local labor	Local & non-local	Local labor	Local labor
Economy	Low-cost	Low-cost	High cost	Moderate
Maintenance	Easy	Easy	Difficult	Easy
Glazing performance	3 mm single glass; high loss	3 mm single glass; high loss	6 mm double glazing (argon); low loss	6 mm double glazing (argon); moderate loss
Building mass (kg)	240,000	180,000	110,000	155,000

6. Conclusion

This study evaluated the thermal performance, structural characteristics, and environmental implications of four representative building typologies—two traditional adobe buildings (with and without thatch coating), a modern reinforced-concrete building, and a proposed hybrid model—under the semi-arid climatic conditions of Isfahan Province. The integrated simulation approach, combining structural analysis (ETABS, SAFE) and dynamic energy modeling (DesignBuilder), enabled a consistent comparison of thermal loads, indoor comfort, and maximum daily temperatures across all models.

The results clearly demonstrate that traditional adobe buildings, particularly those with thatch coating, exhibit superior passive thermal performance. Their high thermal mass and natural insulating layers significantly reduce cooling loads, stabilize indoor temperature fluctuations, and maintain comfort conditions during peak heat periods. However, their structural limitations and vulnerability to seismic and environmental stressors restrict their suitability for contemporary housing.

Modern buildings, while structurally robust and compliant with current safety standards, performed weakest in terms of energy efficiency. Their lightweight walls, higher thermal conductivity, and lack of thermal inertia resulted in the highest cooling loads and the most significant indoor temperature fluctuations. These findings highlight a fundamental performance gap between structural reliability and environmental sustainability in modern construction practices.

The hybrid building model successfully bridges this gap. By combining a reinforced-concrete structural frame with

high-mass brick walls, vernacular spatial organization, improved glazing, and passive cooling features such as courtyards, the hybrid design achieved thermal performance closer to that of traditional structures while maintaining the structural resilience required by modern codes. The use of locally sourced materials further strengthens its environmental and cultural relevance.

Overall, the study concludes that hybrid construction offers a balanced, scalable, and context-appropriate strategy for sustainable building development in Iran's semi-arid regions. It retains the environmental advantages and cultural identity of traditional architecture while meeting the structural and safety demands of contemporary engineering practice. The findings support integrating indigenous building wisdom into modern construction policies and encourage the development of design guidelines that prioritize thermal mass, passive cooling strategies, and improved building envelopes.

Future research may extend this work by exploring hybrid retrofitting strategies for existing buildings, evaluating long-term energy savings through life-cycle assessments, and assessing occupant satisfaction in real-world hybrid prototypes. Such efforts would contribute to the development of a comprehensive framework for climate-responsive, low-carbon architecture rooted in Iran's rich vernacular heritage.

7. Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships.

8. References

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