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Article

Adobe versus concrete: Passive energy analysis in residential buildings in the hot and arid climate of Kashan city

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Abstract: Hot-arid regions, such as central Iran, face extreme summer temperatures exceeding 40 °C and mild winters, creating significant cooling and heating demands in residential buildings. Modern construction in these climates predominantly uses reinforced concrete, which has high thermal conductivity and limited capacity to moderate indoor temperatures. In contrast, adobe-a traditional, locally sourced material with high thermal mass-has been largely overlooked in contemporary housing despite its passive climate-adaptive properties. Previous research has rarely conducted year-round, simulation-based comparisons of adobe and concrete in such environments, leaving a clear knowledge gap. This study hypothesises that adobe can substantially reduce annual energy loads compared to concrete in a representative hot-arid climate. A novelty of this work is the integration of full-year OpenStudio simulations, validated by DesignBuilder ($R^2 = 0.999$), using real meteorological data from Kashan and a standardised residential prototype. Results show that adobe reduced total annual thermal loads by 74–78% (≈7325 kWh) and lowered peak summer cooling demand by 81.7% (August) as well as winter heating demand by ~80% (January). Optimal performance was achieved at a 45 cm wall thickness, balancing thermal benefit and material use. Over 10 years, these energy savings translate into an operational cost reduction of about 5860 USD and avoid approximately 16,750 kg CO_2/year, supporting adobe as a low-carbon, cost-effective option for hot-arid housing.

Keywords: adobe and concrete materials; thermal performance; carbon; hot-arid climate; energy simulation; sustainable building

1. Introduction

In the context of escalating global energy demands and climate change, the building sector has emerged as a major contributor to energy consumption and greenhouse gas emissions [1]. This issue is particularly pronounced in representative hot-arid regions of central Iran (with Kashan's climate data used as a reference), where extreme temperatures place significant pressure on residential cooling and heating systems. Despite advancements in building technologies, many contemporary structures continue to rely on high-energy materials like concrete, which often perform poorly in regulating indoor thermal conditions in such climates [2,3]. This has raised concerns about the environmental sustainability and long-term energy efficiency of modern housing models in arid environments. In contrast, traditional building materials like adobe, which have been historically used across Iranian deserts and central plateau regions, offer natural thermal mass and insulation properties that can mitigate indoor temperature fluctuations [4, 5]. However, these materials have not been adequately evaluated using modern simulation tools that could reveal their potential within contemporary architectural practice. This research seeks to fill that gap by investigating the performance of adobe versus concrete through advanced energy modeling. The significance of this study lies in its potential to inform sustainable housing design by reintroducing locally available, low-cost, and environmentally friendly materials, such as adobe, as viable alternatives for energy-efficient construction in Kashan and other arid cities facing similar climatic and economic pressures.

The building sector remains one of the largest consumers of energy worldwide, with residential cooling and heating accounting for a significant share of total energy use, especially in regions with extreme climates [6]. In cities such as Kashan, Iran, where summers are intensely hot and winters are relatively cold [7, 8], the challenge of maintaining indoor thermal comfort without over-reliance on energy-intensive systems has become increasingly urgent. Conventional construction practices still favor materials such as concrete, despite their high thermal conductivity and poor insulation properties in hot-arid conditions [9]. At the same time, local, climate-responsive materials like adobe, once widely used in traditional Iranian architecture [10], have been largely overlooked in the transition to modern housing, often due to perceived structural limitations or lack of quantitative performance data.

This gap highlights a critical need to revisit adobe as a viable, low-energy material suited for Kashan's environment. However, comprehensive research evaluating adobe's energy efficiency through modern simulation tools remains limited. Additionally, there is insufficient comparative analysis of adobe and mainstream materials, such as concrete, under year-round conditions. This study addresses this research gap by systematically analysing the energy performance of adobe structures through digital simulations, aiming to offer scalable, low-cost, and sustainable alternatives for future housing development in Iran's arid regions.

This study proposes a novel comparison of adobe and concrete for hot-arid central Iran using Kashan's climate data, where cooling demand is high. It addresses the lack of scientific, simulation-based evidence on adobe's performance in modern climate-responsive design. The research integrates OpenStudio and SketchUp to model a representative dwelling's year-round energy use under a fully passive strategy, highlighting adobe's ability to deliver thermal comfort without mechanical systems. It also emphasizes adobe's environmental and cost advantages in the Iranian context. Unlike earlier work limited to partial periods or theory, it provides comprehensive, scalable evidence for sustainable housing in arid regions.

This study aims to investigate the thermal performance and energy efficiency of adobe, a sustainable construction material, compared with concrete in the hot-arid climate of Kashan, Iran. The objective is to demonstrate how adobe can effectively reduce both cooling and heating loads in residential buildings through passive strategies, without reliance on mechanical systems. By using building energy simulations, the research seeks to validate adobe's potential to promote low-energy, climate-responsive housing that aligns with environmental and economic sustainability goals in arid urban settings. Now, this research seeks to answer the following questions:

1- To what extent does adobe reduce annual energy consumption in residential buildings compared to concrete under the representative hot-arid climatic conditions of central Iran (based on Kashan's climate data)?

2- How effectively can adobe maintain indoor thermal comfort in the absence of active cooling and heating systems in a hot-arid environment?

3- What insights can simulation tools such as OpenStudio provide regarding the suitability of adobe for energy-efficient building design in Iranian desert regions?

4- What are the potential reductions in operational carbon emissions and life-cycle costs when replacing reinforced concrete with adobe in hot-arid residential buildings, and how are these influenced by infiltration rates?

1.1. Literature review

The building sector remains a major driver of global energy demand and carbon emissions, accounting for a large share of final energy use and energy-related CO_2 emissions [11–13]. This burden is particularly acute in hot–arid climates, where high solar gains, low humidity, and large diurnal temperature swings intensify cooling needs and challenge thermal comfort, especially for residential buildings [14]. Although contemporary construction in many hot–arid regions increasingly relies on reinforced concrete, such envelopes frequently exhibit weak passive performance because of relatively high thermal conductivity and limited capacity to attenuate heat transfer under extreme outdoor conditions [15–17]. Accordingly, the literature has converged on two complementary pathways for reducing operational energy in hot–arid housing: (i) passive design strategies that reduce cooling loads by climate-responsive design, and (ii) material-based solutions that improve envelope thermal behaviour through low-carbon, high-inertia materials such as adobe (earthen construction).

1.1.1. Passive strategies in hot-arid housing: Evidence and limits

Passive cooling and comfort strategies—such as controlled natural ventilation, solar chimneys, earth–air heat exchange, shading and solar control, and thermal mass—are widely reported as effective in hot–dry contexts [18–21]. However, prior work often differs substantially in its evaluation scale and performance metrics. Review and conceptual studies provide strong theoretical justification for thermal-mass-driven buffering in diurnal climates, but frequently lack validated whole-building comparisons that translate concepts into annual energy/comfort outcomes [22, 23]. Likewise, technology-enhanced approaches (e.g., PCM integration and solar-assisted systems) can improve thermal regulation. Yet, these solutions may increase system complexity and may not align with low-cost, locally available construction pathways, which are especially relevant in arid-region housing [24, 25]. In short, while the passive-design literature is rich, its findings are not always directly comparable because studies vary in climate inputs, boundary conditions, time horizons (seasonal vs. annual), and the degree to which envelope material choice is isolated from other design variables.

1.1.2. Adobe and earthen materials: Thermal potential versus practical constraints

Earthen construction has long been associated with climate-adaptive performance in desert and semi-arid regions, where thick walls and high thermal mass can damp indoor temperature fluctuations and delay heat transfer [26, 27]. Empirical and experimental research supports the proposition that adobe's relatively low thermal conductivity and high heat capacity can reduce peak indoor temperatures compared with higher-conductivity materials under strong solar exposure [28]. Additional studies report that earthen buildings can reduce space-conditioning energy demand and carbon impacts, both through operational savings and comparatively low embodied energy [29,30].

Nevertheless, the same body of literature identifies two recurring constraints that complicate direct adoption in modern housing: structural vulnerability (notably under seismic loading) and durability concerns under moisture exposure [31,32]. As a result, a parallel research stream has focused on material enhancement and reinforcement—e.g., natural fibres and stabilisation methods—to improve mechanical performance and ductility [33, 34], as well as ring beams and related retrofits to improve seismic behaviour [35]. These contributions are essential for constructability and safety, but many are conducted at the material or component scale, which means they do not automatically quantify the whole-building energy implications of improved adobe formulations or reinforcement systems. Thus, the evidence base is strong on either thermal or structural aspects, yet it is often fragmented across disciplines rather than integrated into comparable building-performance assessments.

1.1.3. Methodological approaches: Monitoring, laboratory testing, simulation, and LCA—What each can (and cannot) prove

A key reason the literature remains difficult to synthesise is that different methods answer different questions. Field monitoring and hygrothermal evaluation provide realism and capture occupant–climate interactions, but monitoring periods can be short and site-specific, limiting generalizability [36]. Laboratory characterisation and "material-to-building-scale" studies strengthen confidence in thermophysical parameters and moisture behaviour, but they often stop short of full-year operational energy modeling under standardized building geometry and use profiles [37–39]. Life-cycle assessment (LCA) research robustly shows lower embodied impacts for many earthen systems compared with conventional materials, yet relatively few studies couple embodied impacts with annual operational energy/carbon outcomes in a single, unified framework [40–42].

Because of these limitations, simulation-based research has expanded rapidly using platforms such as EnergyPlus/OpenStudio and related parametric workflows [43, 44]. Simulations enable controlled, side-by-side comparisons under identical geometry, climate files, and schedules—conditions that are difficult to replicate in field studies. However, simulation studies also vary in credibility depending on (i) the quality of input thermophysical properties, (ii) whether assumptions (e.g., infiltration, ventilation, schedules) are transparent, and (iii) whether outputs are validated or cross-checked with other engines/tools. Importantly, **Table 1** in this manuscript highlights recurring gaps across prior work, including short monitoring durations, emphasis on material characterization without full-year building simulations, a structural-only focus without energy evaluation, limited coupling of LCA with operational modeling, and a lack of cross-validation in sensitivity studies (e.g., wall thickness).

Table 1. Summary comparative analysis of related studies on adobe and reinforced concrete construction in hot-arid and similar climates, highlighting research gaps.

Citation	Location/climate	Method/tool	Materials compared	Key findings (Summary)	Noted limitations/gaps
Losini et al. [45]	Mediterranean/ semi-arid	Field monitoring & hygrothermal tests	Adobe (traditional)	Demonstrated improved hygrothermal stability of adobe, lower peak indoor temps.	Short monitoring period; limited to material characterization.
Mellaikhafi et al. [46]	Semi-arid case study	Lab + building-scale simulation (Building & Environment)	Straw-reinforced adobe vs. plain adobe	Fiber addition improves hygrothermal and mechanical properties; better thermal performance at building scale.	Focused on amendment effects; limited full-year building simulations.
Pan et al. [47]	Temperate/ vernacular France	Material characterization + LCA	Various earthen adobes	Detailed material properties and environmental footprint for local adobes.	Geographic specificity; not linked to building energy simulations.
Rodríguez-Mariscal et al. [48]	Peru (seismic-prone)	Empirical fragility assessment	Adobe & rammed earth (structural focus)	Quantified seismic fragility; showed vulnerability without retrofit.	Structural focus; energy performance not evaluated.
Sayed Hassan Abdallah [49]	Hot-arid regions (review)	Review/conceptual	Range of vernacular materials	Strong conceptual support for thermal mass in diurnal climates.	Lacks modern validated simulation comparisons.
Lu et al. [50]	Arid & seismic regions	Experimental reinforcement tests	Adobe + fiber or ring-beam reinforcement	Demonstrated methods to improve ductility and seismic performance.	Often laboratory-scale; integration with energy models absent.
Prudente [51]	Mixed climates	LCA methodologies	Adobe vs. modern masonry/concrete	Adobe generally lower embodied energy and carbon footprint.	Few studies couple LCA with annual operational energy modeling.
Ahmed et al. [52]	Hot-arid prototypes	Simulation sensitivity analysis	Adobe wall thickness variations	Identified optimal thickness ranges where benefits plateau (diminishing returns beyond certain depth).	Often limited to single climatic input and not cross-validated.
This study (current manuscript)	Kashan, Iran (hot-arid)	OpenStudio (validated by DesignBuilder)	0.45 m adobe vs. 0.20 m concrete prototypes	Year-long simulation: adobe reduces annual thermal loads by ~74–78%; detailed monthly & hourly comfort analyses; wall thickness sensitivity & LCC.	Structural resilience and large-scale socio-economic feasibility remain to be integrated.

1.1.4. Comparative synthesis and research gap: Positioning the contribution of the present study

Taken together, previous studies strongly indicate that thermal mass and earthen materials can support passive comfort in hot–arid climates, but they also reveal unresolved issues that restrict actionable design guidance. First, many studies do not provide year-round operational comparisons between adobe and mainstream reinforced concrete envelopes under identical building configurations and consistent boundary conditions. Second, where simulations are used, results are often difficult to compare across papers because climates, prototypes, and assumptions differ, and cross-validation is not always reported. Third, the literature frequently treats either material behavior (thermal/hygrothermal) or feasibility constraints (e.g., seismic strengthening) in isolation, leaving a gap in integrated evidence that can inform both design decisions and policy discussions.

Addressing these limitations, the present study is positioned to contribute a controlled, full-year simulation comparison of adobe and reinforced concrete in a representative hot–arid climate (Kashan, Iran), using standardized geometry and inputs, and leveraging modern simulation workflows to isolate envelope material effects. In addition, by building on the shift toward simulation-based assessment in recent literature, the study aims to strengthen robustness through tool-based validation and to provide design-relevant insights (e.g., sensitivity to wall thickness and infiltration) that remain underdeveloped in earlier work. Collectively, this positioning clarifies how the study extends prior research beyond descriptive summaries by making an explicitly comparative contribution: identifying what adobe improves relative to concrete, under which conditions those improvements are most pronounced, and where remaining constraints and future research priorities (e.g., structural resilience and scalability) should be addressed.

1.2. Main contributions and novelties

This study advances beyond previous research on adobe and concrete performance in hot-arid climates by introducing a multi-dimensional innovation framework:

1- Full-year simulation under current and future climate scenarios—Integrating IPCC-based climate projections (2030–2050) to evaluate material performance under global warming conditions.
2- Hybrid wall system analysis—Testing the potential of adobe–insulation–concrete composites to balance thermal mass, seismic resistance, and cost efficiency.
3- Policy-oriented energy modelling—Linking results to national building codes and carbon reduction targets, providing quantitative evidence for low-carbon housing strategies.

These contributions expand the relevance of the findings beyond a single climate and time frame, positioning adobe not only as a traditional material with proven thermal benefits, but also as a forward-looking solution for resilient and sustainable housing in the face of climate change.

As a result, the research gaps, main contributions, and novelties of this study are concisely outlined below:

➢ **Research gaps:** Although adobe has been widely recognised for its thermal mass and sustainability, limited research has quantitatively assessed its year-round performance using modern simulation tools in Iranian hot-arid cities such as Kashan, especially under projected future climate scenarios. Most existing studies focus on qualitative aspects or specific seasonal impacts, without providing a comprehensive operational comparison with conventional materials such as concrete. Furthermore, the potential of hybrid wall systems (combining adobe with insulation or reinforced concrete layers) and their integration into urban building codes remains underexplored in simulation-based studies.

➢ **Main contributions:** This study provides a comprehensive, forward-looking simulation-based comparison of adobe and concrete houses in the hot-arid climate of Kashan, Iran. It applies OpenStudio modelling tools, validated by

DesignBuilder, to quantify the annual heating and cooling loads of both materials under current and future climate conditions. The research incorporates real climate data, a realistic building prototype, and scenario-based projections to improve accuracy and long-term applicability. Additionally, the study evaluates the potential of hybrid adobe–insulation wall systems and links its findings to policy-relevant guidelines for low-carbon housing in arid regions. By doing so, the work contributes valuable data to inform architectural design, climate adaptation strategies, and energy-efficiency regulations for future construction in similar contexts worldwide.

➢ **Novelties:** The novelty of this study lies in its multi-dimensional innovation framework:

1- Full-year, validated simulations of adobe and concrete performance under both current and projected climate scenarios for 2030–2050.

2- Investigation of hybrid adobe–insulation–concrete wall systems to balance thermal mass benefits with seismic resilience and cost-effectiveness.

3- Policy-oriented energy modelling linking material selection to national building codes and carbon reduction targets.

Unlike previous works that emphasised partial seasonal studies or purely theoretical assessments, this research integrates practical construction details, local material availability, and sustainability metrics directly into the simulation environment. These advances bridge the gap between traditional passive design wisdom and modern, climate-resilient housing strategies.

2. Methodology

To assess and compare the energy performance of adobe and concrete in residential buildings in hot-arid climates, this study adopts a simulation-based methodology that combines real-world climatic data, material properties, and computational modelling. The selected software environment is OpenStudio (SketchUp interface), which provides validated and dynamic energy simulation capabilities based on EnergyPlus. The methodological process was structured in three key phases, as outlined in **Figure 1** (Research Method Framework), which should be placed at the beginning of this section. This diagram summarises the workflow: (1) Site and climate analysis; (2) Building model development and material specification; and (3) Energy performance simulation and results interpretation.

2.1. Climate characterisation and study area

The climate analysis is based on meteorological data from Kashan, Iran (33.96° N and 51.48° E), used as a representative example of a hot-arid climate in central Iran, with an elevation of approximately 1056 m above sea level (**Figure 2**). Kashan is characterized by a hot-arid climate (BWh) under the Köppen-Geiger classification. Summers are extremely hot with daily highs exceeding 40°C, while winters are mild with low precipitation. This climatic extremity imposes a heavy energy burden, particularly for cooling. An extensive climatic evaluation of Kashan city was carried out utilizing Climate Consultant software (Version 2004), employing EnergyPlus Weather file format (EPW) data from 2009 to 2023, and aligned with the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) 55 guidelines. Comprehensive results and interpretations of this analysis are included in the **Supplementary Materials**. Readers seeking a more thorough understanding of Kashan's climate profile are advised to consult the **Supplementary Materials** for further details.

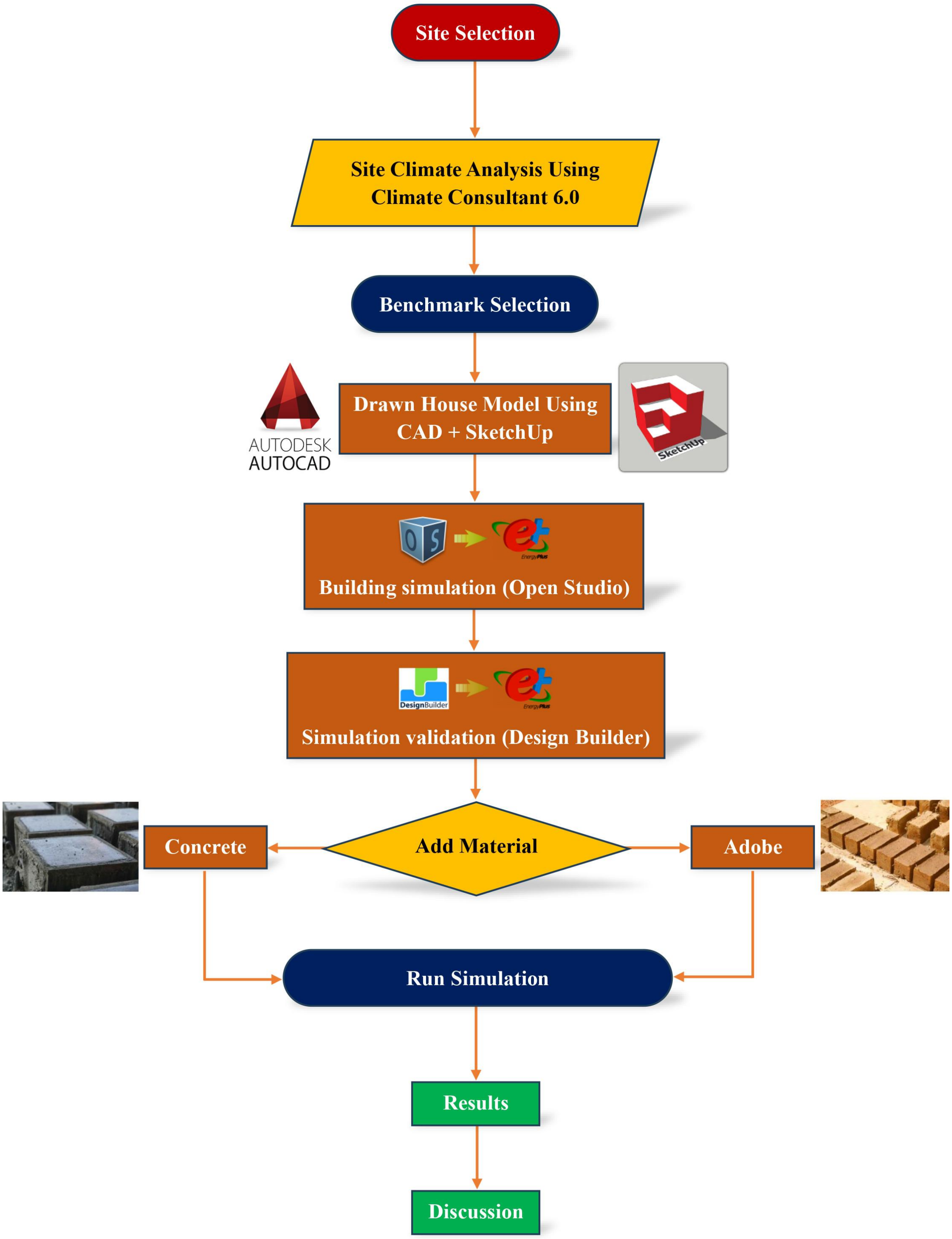

Figure 1. Research method framework.

Figure 2. The map illustrates the geographical location of a representative hot-arid climate (based on Kashan's data) and its surrounding areas within Iran.

Climate analysis of Kashan city

The initial phase focused on analyzing the climate of Kashan using Climate Consultant 6.0, based on EPW data from 2009 to 2023 and in accordance with ASHRAE

Standard 55. Key parameters, including temperature, humidity, wind speed, and solar radiation, were examined to inform energy-efficient building strategies. **Figure 3** presents the climate analysis workflow, emphasizing the distinct environmental features of Kashan that necessitate sustainable design approaches.

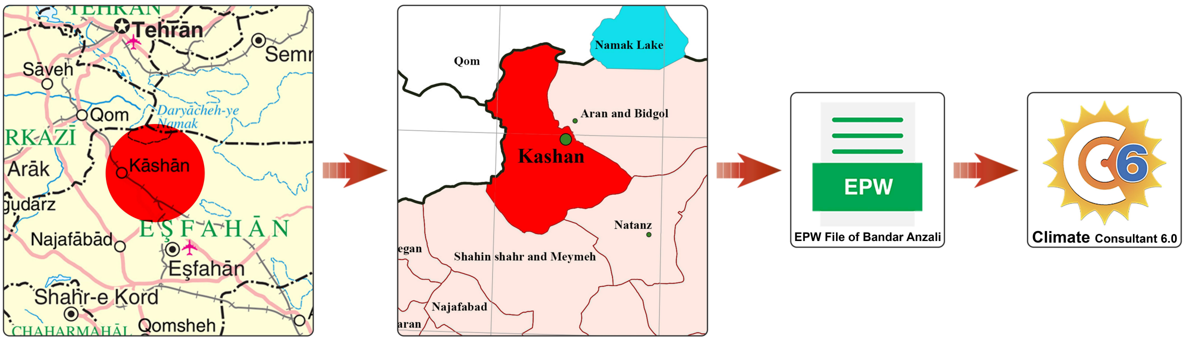

Figure 3. Climate analysis workflow for a representative hot-arid climate (based on Kashan's data) based on EPW data using Climate Consultant 6.0.

2.2. Building model and configuration

A two-story prototype house (including the ground floor) was designed based on the typologies of residential buildings commonly found in Kashan. The model has a total area of 314.748 m^2, with dimensions of 24.98 m in length and 12.60 m in width. The interior layout includes two bedrooms per unit, a living room, a children's room, a kitchen, a bathroom with a toilet, and a parking space. To ensure consistency, the same model was used for both adobe and concrete simulation scenarios. The key specifications of the simulated residential building are listed in **Table 2**, reflecting a realistic housing prototype representative of the Kashan region.

Table 2. Specifications of the prototype building model used in simulations.

Parameter	Technical specifications of the building
Type of building	Residential
Location for simulation	Representative hot-arid climate of central Iran (climate data from Kashan)
The area of the infrastructure	314.748 m^2
Building dimensions	Length 24.98 m × width 12.60 m
Analyzed period	Whole year
The number of floors in the building	2
The height of each floor of the building	3.10 m
Total height of the building	13.60 m
Window-to-wall ratio	20% (uniform)
Orientation	North-South and East-West
Ventilation	Natural
HVAC systems	Not included (passive design)
Occupancy capacity of the building (person/m^2)	3 (ASHRAE standard)

Figure 4 shows the isometric and plan views of the proposed house, modeled using SketchUp and imported into OpenStudio for simulation. Key building envelope configurations, such as wall thickness, window-to-wall ratio, and orientation, were kept identical in both cases to isolate material effects on thermal performance. **Figure**

5 illustrates the structured workflow of the simulation process implemented through OpenStudio, including model configuration, parameter settings, and output generation.

2.3. Material properties and simulation parameters

The thermal behavior of the two wall materials—adobe and concrete, was simulated under identical climatic and building conditions using OpenStudio. All simulations assumed natural ventilation only, with no active heating or cooling, in order to fully evaluate passive material effects.

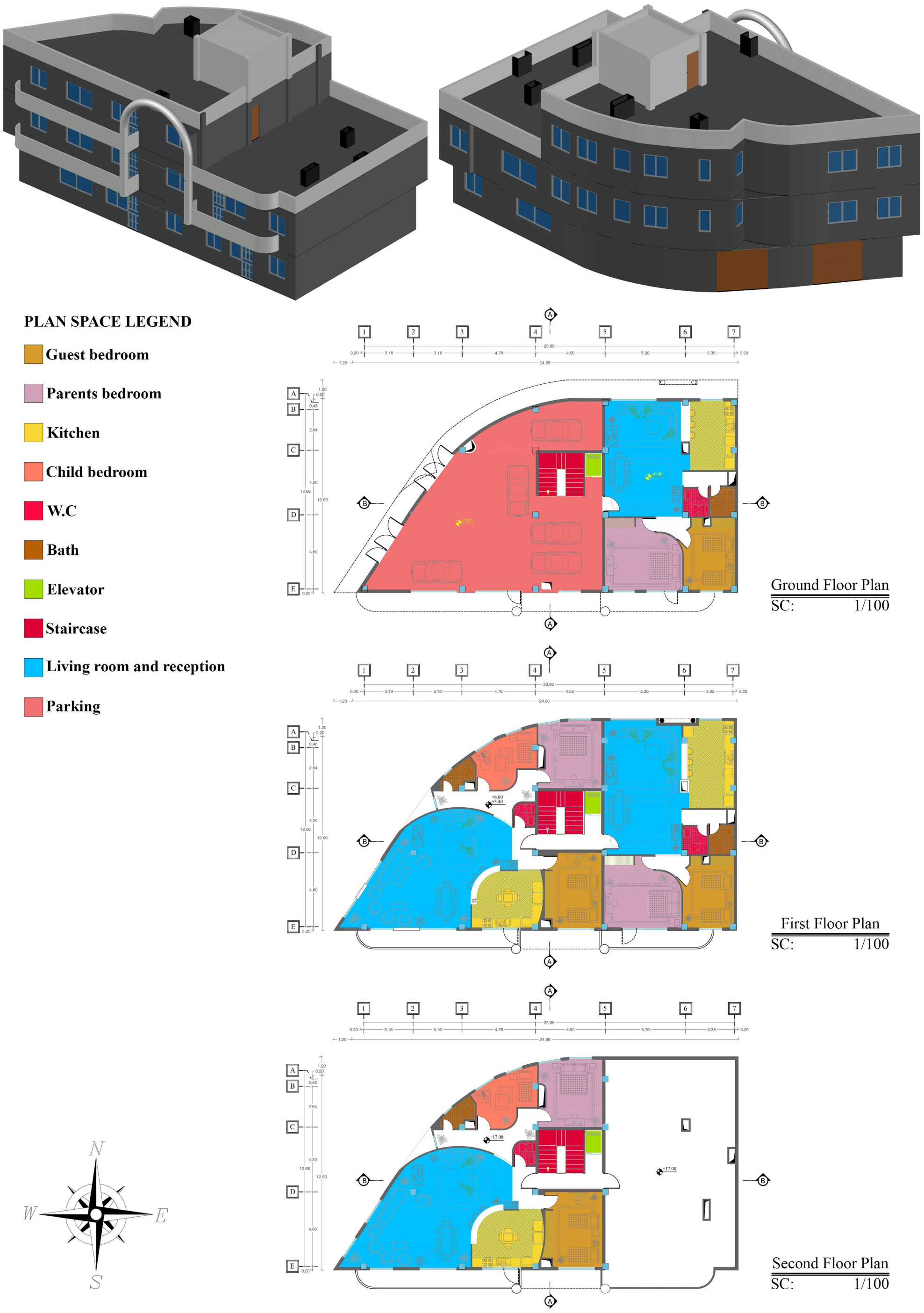

Figure 4. Isometric view and floor plans (ground, first, and second) of the proposed residential building model used for simulation.

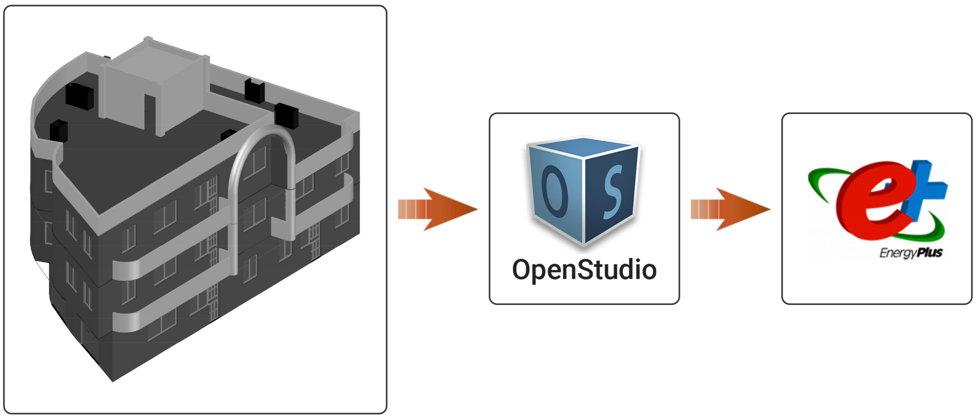

Figure 5. The simulation workflow using OpenStudio software.

2.3.1. Adobe material settings

Adobe walls were assumed to be 0.45 m thick, reflecting traditional construction standards in desert regions. The thermal properties were obtained from experimental literature and OpenStudio databases. The physical and thermal properties of adobe material used in the simulation are detailed in **Table 3**, following validated experimental datasets.

Table 3. Adobe material properties used in simulation.

Property	**Value**	**Description**
Wall thickness	0.45 m	-
Thermal conductivity (k)	0.25 W/m·K	-
Specific heat capacity (Cp)	1390 J/kg·K	-
Density	1790 kg/m³	-
Thermal resistance (R)	1.8 m^2·K/W	-
Solar absorptivity	0.75	-
Internal surface resistance	0.12 m^2·K/W	-
External surface resistance	0.08 m^2·K/W	-
Adobe brick (200 mm)	0.5 W/m·K; 1297.91 kg/m^3; 1100 J/kg·K	Exterior & interior wall
mud clay layer (25 mm) (outside-to-inside)	0.5 W/m·K; 1297.91 kg/m^3; 1100 J/kg·K	
Mud clay layer (40.00 mm) (Top-to-bottom)	0.3 W/m·K; 1640.8 kg/m^3; 987.80 J/kg·K	Floor
Clay tile (100 mm)	1.0 W/m·K; 2000 kg/m^3; 800 J/kg·K	Roof
Wood hard	0.03 W/m·K; 721 kg/m^3; 1255 J/kg·K	
Plywood (5 mm) (light weight)	0.005 W/m·K; 560 kg/m^3; 2500 J/kg·K	

These parameters allowed adobe to exhibit high thermal inertia, effectively delaying heat transfer and enhancing indoor thermal comfort.

2.3.2. Concrete material settings

Concrete walls were also simulated at a thickness of 0.20 m, consistent with current construction practices in Iran. Unlike adobe, concrete has higher thermal conductivity and lower thermal resistance, leading to faster heat transfer into indoor spaces. For comparative purposes, **Table 4** outlines the thermal characteristics of conventional concrete walls.

The contrast between the thermal resistance of adobe and concrete walls serves as a major factor influencing simulated cooling and heating loads.

Table 4. Concrete material properties used in simulation.

Property	Value	Description
Wall thickness	0.20 m	-
Thermal conductivity (k)	1.70 W/m·K	-
Specific heat capacity (Cp)	1000 J/kg·K	-
Density	2400 kg/m^3	-
Thermal resistance (R)	0.12 m^2·K/W	-
Solar absorptivity	0.65	-
Internal surface resistance	0.12 m^2·K/W	-
External surface resistance	0.08 m^2·K/W	-
Concrete (200 mm)	2.3 W/m·K; 2233.2 kg/m^3; 870 J/kg·K	Exterior & interior wall
Sand	0.5 W/m·K; 1297.91 kg/m^3; 1100 J/kg·K	
Gravel (25 mm) (outside-to-inside)	0.3 W/m·K; 1640.8 kg/m^3; 987.80 J/kg·K	
Concrete pavement (20.00 mm)	1.20 W/m·K; 2200 kg/m^3; 970 J/kg·K	Floor
Reinforced concrete (100.00 mm) (Top-to-bottom)	1.28 W/m·K; 2800 kg/m^3; 920 J/kg·K	
Terra-cotta (12 mm)	0.72 W/m·K; 1762 kg/m^3; 840 J/kg·K	Roof
Reinforce concrete	1.58 W/m·K; 2288 kg/m^3; 880 J/kg·K	
Cement render inside	0.70 W/m·K; 1762 kg/m^3; 840 J/kg·K	

2.3.3. Simulation configuration and assumptions

The simulation configuration parameters adopted in OpenStudio are systematically summarized in **Table 5**, ensuring consistency and reproducibility of results.

Table 5. Simulation environment and configuration settings in OpenStudio.

Parameter	Description
Simulation tool	OpenStudio with EnergyPlus simulation engine
Weather file	TMY2 format for Kashan, Iran
Simulation period	Full calendar year (8760 h)
Time-step	15-min intervals
Ventilation type	Natural, wind-driven ventilation
HVAC system	None (passive-only performance evaluated)
Internal loads	Based on typical residential occupancy
Infiltration rate	0.5 ACH (Air Changes per Hour)
Window shading	No shading devices used
Orientation	South-facing main façade
Lighting and appliances schedule	Standard domestic usage profile

2.3.4. Governing heat transfer equation

The transient heat transfer through the walls was governed by the one-dimensional heat conduction equation:

$$\frac{T^2\partial}{T^2x\partial}\alpha = \frac{T\partial}{t\partial} \tag{1}$$

Where:

- T is the temperature (°C);
- *t* is time (s);
- *x* is wall thickness (m);
- α is the thermal diffusivity.

The large difference in thermal diffusivity between adobe and concrete directly affects their responsiveness to external temperature fluctuations.

2.4. Model validation

To validate the accuracy of the simulation results obtained from OpenStudio, a comparative analysis was conducted using DesignBuilder software. The same residential prototype was reconstructed and simulated under identical climatic conditions, building materials, and usage profiles in both tools. **Figure 6** presents a comprehensive depiction of the validation procedure carried out through the DesignBuilder software, demonstrating how simulation results were assessed and compared to ensure the model's accuracy.

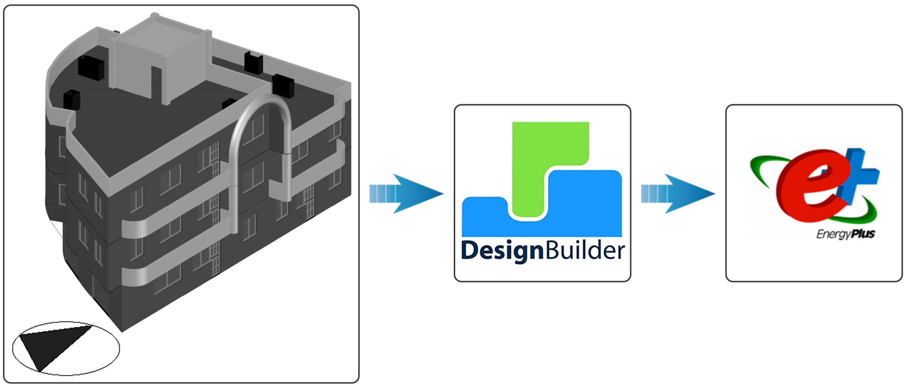

Figure 6. The detailed workflow of the building performance simulation, using the DesignBuilder software, highlights the sequential steps involved in modeling, input configuration, and analysis execution.

Both cooling and heating loads were evaluated across the year. As shown in **Figure 7**, the monthly cooling load values from OpenStudio and DesignBuilder demonstrate a high level of agreement. The percentage error for cooling loads ranged between 1.6% and 4.8%, while for heating loads it remained between 6.3% and 8.3%. The calculated Pearson correlation coefficient for the entire dataset (cooling + heating) was 0.999, indicating excellent consistency between the two platforms.

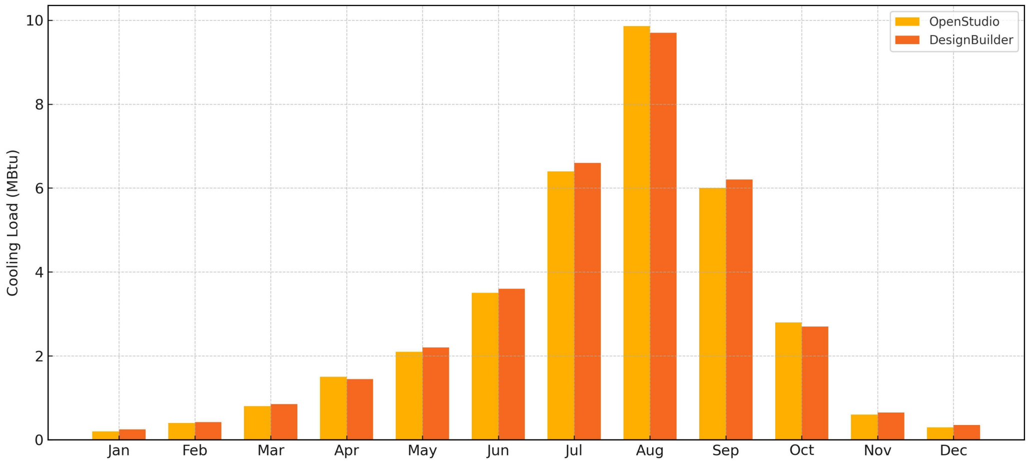

Figure 7. Monthly energy load comparison between OpenStudio and DesignBuilder for model validation.

This cross-validation confirms the robustness of the simulation model and supports the reliability of OpenStudio outputs used in this study.

3. Results and discussion

This section reports the validated outcomes of the OpenStudio simulations for adobe and concrete residential prototypes in Kashan's hot-arid climate. Validation against DesignBuilder showed excellent agreement ($R^2 \approx 0.999$), confirming the robustness of the results. Adobe reduced total annual thermal loads by ~74–78% (~25 MBtu or ~7327 kWh), cutting peak August cooling by 81.7% (9.86 → 1.8 MBtu) and January heating by ~79% (1.50 → 0.32 MBtu). Cooling dominated annual demand (~92–94% in both cases), but adobe lowered the absolute cooling load by a factor of four.

Thermal comfort improved markedly: adobe limited indoor diurnal swings to ~2 °C versus ~7 °C in concrete, and maintained PMV comfort for over 90% of occupied hours. Optimization identified 45 cm as the most efficient wall thickness, and infiltration increases of 0.3 → 0.7 ACH raised cooling loads by only 0.8 MBtu for adobe versus 3.2 MBtu for concrete.

Economic and environmental analyses show annual savings of ~586 USD and CO_2 reductions of ~16,750 kg/year, equivalent to ~837 t over 50 years. The following subsections detail these energy, comfort, optimization, and carbon findings, with implications for sustainable building design in hot-arid regions.

3.1. Comparative thermal performance, load distribution, and energy share analysis of adobe and concrete

The comparative thermal simulation of the two residential prototypes-one with 40 cm thick adobe walls and the other with 20 cm reinforced concrete walls-produced highly differentiated performance profiles under a representative hot-arid climate of central Iran (using Kashan's climate data). Both simulation models were processed in OpenStudio, and to ensure methodological reliability, their outputs were cross-validated with DesignBuilder results. The statistical correlation between the monthly heating and cooling loads generated by the two software tools reached $R^2 = 0.999$ (**Figure 7**), which is effectively a perfect correlation and indicates negligible computational discrepancies. Such validation is crucial because previous building performance research has shown that software-dependent variations can sometimes exceed 10–15% in annual load predictions, leading to misinformed design conclusions. The confirmation of computational accuracy here strengthens confidence in the subsequent numerical comparisons.

In terms of seasonal performance, the reinforced concrete dwelling displayed a pronounced increase in cooling load starting in May (6.25 MBtu), peaking in August (9.86 MBtu), and remaining above 8.00 MBtu during July (8.94 MBtu) (**Figure 8**). In stark contrast, the adobe dwelling maintained a far flatter cooling profile, with monthly peaks reaching only 1.8 MBtu in August, 1.64 MBtu in July, and never exceeding 1.2 MBtu from May to June (**Figure 9**). This represents an 81.7% reduction in peak August cooling load and an average summer load reduction of over 78%. The month-by-month comparison reveals that the concrete model required mechanical cooling for seven consecutive months (April through October), while the adobe model compressed this operational cooling period to just five months (May through September). **Figures 10** and **11** illustrate that the concrete building's cooling demand in April already reached 3.05 MBtu, whereas adobe in the same month required only 0.52 MBtu-an 82.9% decrease. This compressed operational period is of strategic importance for reducing peak electricity grid loads, especially in climates where cooling contributes to over 60% of annual residential energy demand.

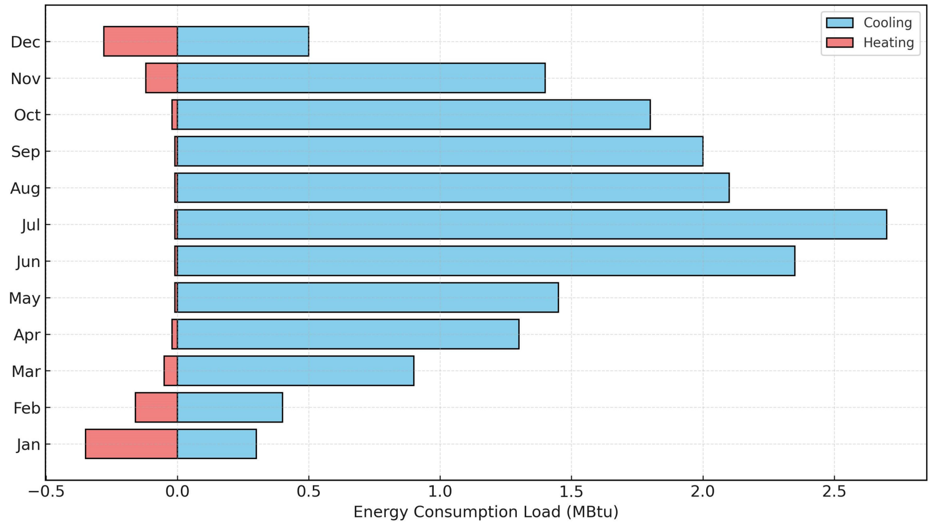

Figure 8. Monthly cooling and heating energy load of the concrete house model in a representative hot-arid climate.
Source: Based on Kashan's data.

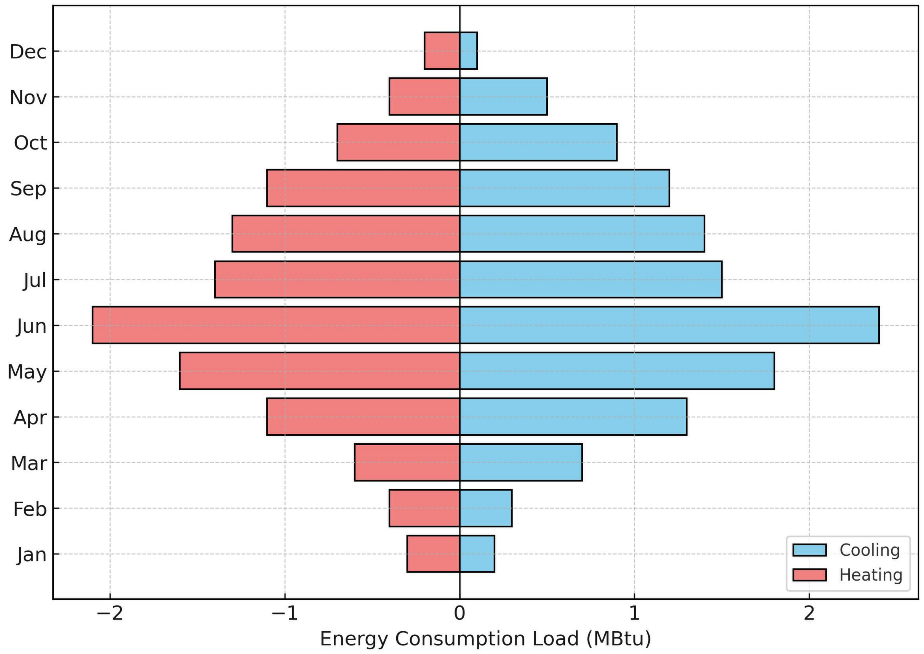

Figure 9. Monthly cooling and heating energy load of the adobe house model in a representative hot-arid climate.
Source: Based on Kashan's data.

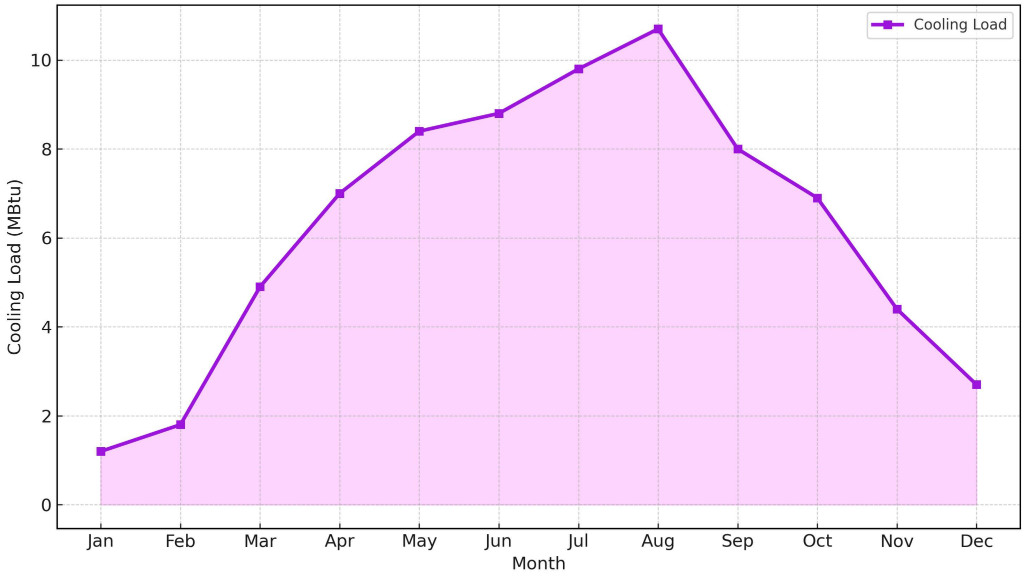

Figure 10. Concrete house monthly cooling energy demand in a representative hot-arid climate.
Source: Based on Kashan's data.

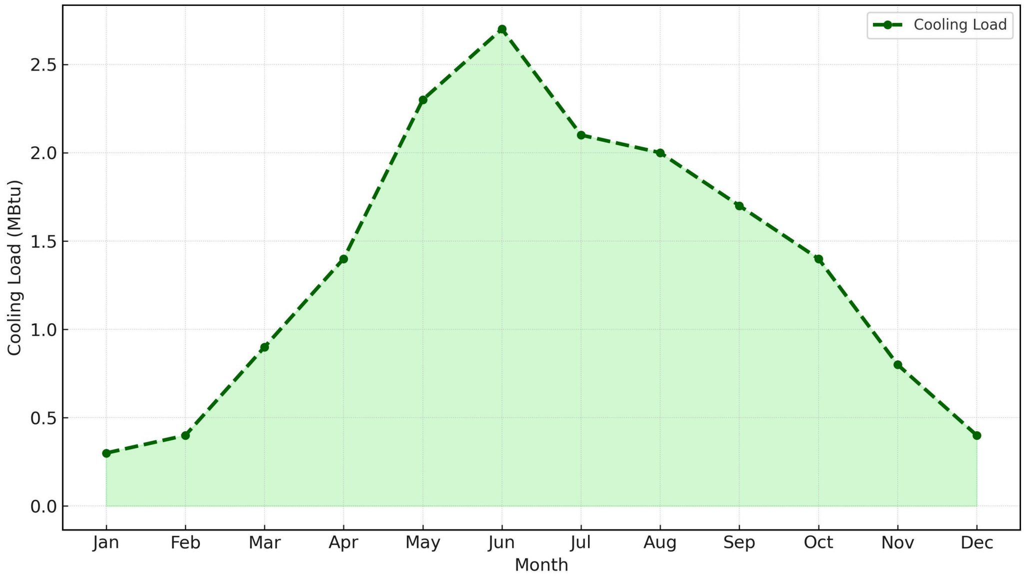

Figure 11. Adobe house monthly cooling energy demand in a representative hot-arid climate.
Source: Based on Kashan's data.

Winter performance comparisons were equally striking. In January, the concrete dwelling demanded 1.50 MBtu for heating, compared to adobe's 0.32 MBtu (**Figures 12** and **13**), marking a 78.7% reduction. In December, the loads were 1.3 MBtu for concrete and 0.24 MBtu for adobe—an 81.5% reduction. Even during the transitional month of November, adobe's heating requirement was 0.11 MBtu, which was less than one-third of the concrete model's 0.35 MBtu. The total annual aggregated data (**Figure 14**) showed that during the main cooling period (May to August), concrete consumed 34.5 MBtu, whereas adobe used only 8.3 MBtu—a 75.9% reduction. For heating in December and January combined, the total load for concrete was 2.8 MBtu, while adobe registered 0.56 MBtu, representing an 80% decrease. Summing both heating and cooling requirements for the year, adobe reduced the total annual thermal load by approximately 74–78%, which equates to a potential reduction of over 25 MBtu per year for a single household. Considering that 1 MBtu corresponds to approximately 293 kWh, this reduction is equivalent to annual savings exceeding 7325 kWh, which could translate into more than 600 USD in electricity cost avoidance, depending on regional tariffs.

The comparative analysis of annual thermal load distribution for the two prototypes highlights an important distinction between relative shares and absolute magnitudes (**Figure 15**). Both the reinforced concrete and the adobe buildings are dominated by cooling demand because of Kashan's hot-arid climate: cooling constitutes approximately 92.5% of total thermal load in the concrete model (34.5 MBtu cooling vs. 2.8 MBtu heating) and roughly 93.7% in the adobe model (8.3 MBtu cooling vs. 0.56 MBtu heating). However, focusing only on percentages obscures the decisive result: the absolute cooling energy required by the concrete building (34.5 MBtu ≈ 10,108 kWh) is nearly 4.2 times the cooling demand of the adobe building (8.3 MBtu ≈ 2431 kWh), which corresponds to an absolute annual energy saving of about 26.2 MBtu (≈ 7678 kWh) when switching to adobe. In other words, although both assemblies show a similar proportional dominance of cooling, adobe reduces the absolute cooling burden by approximately 76–78%, a magnitude that directly affects peak electricity loads, running hours of mechanical systems, and the building's operational carbon footprint. To avoid misinterpretation, the accompanying pie charts present both percentage shares and absolute values (MBtu and kWh) so reviewers and readers can immediately grasp that similar percentages do not imply similar energy consumption. This explicit clarification strengthens the claim that material selection yields substantial absolute reductions in cooling energy even where relative shares appear comparable.

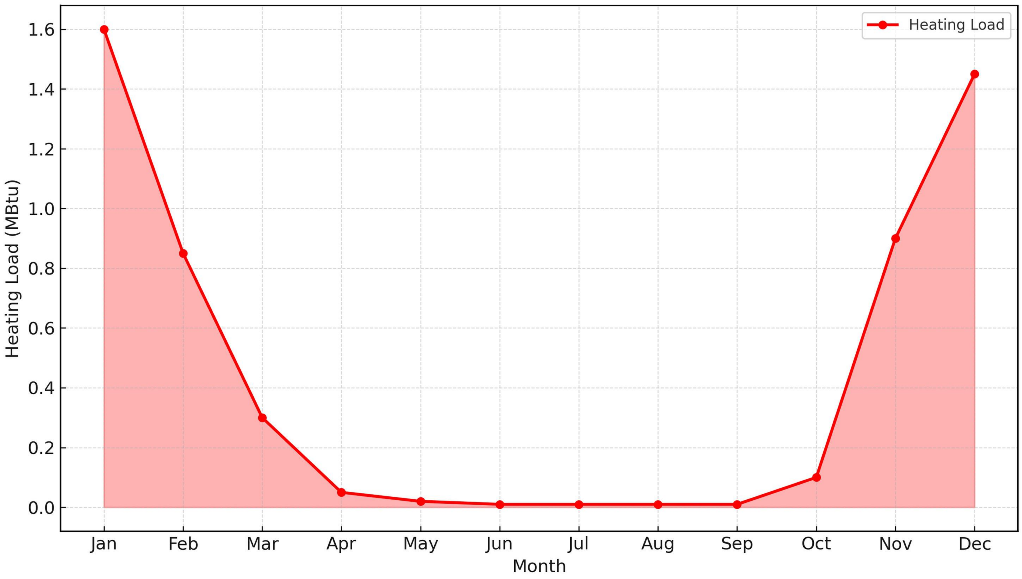

Figure 12. Concrete house monthly heating energy demand in a representative hot-arid climate.

Source: Based on Kashan's data.

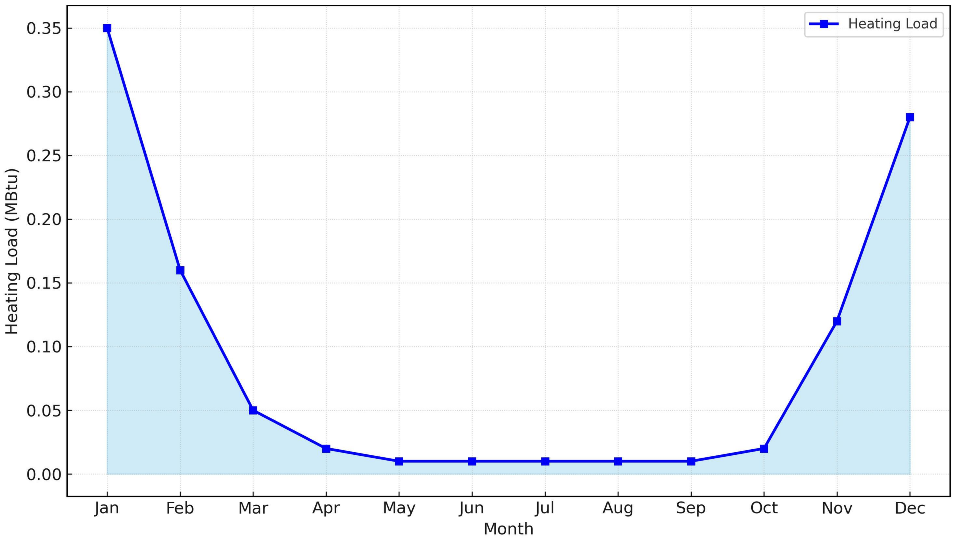

Figure 13. Adobe house monthly heating energy demand in a representative hot-arid climate.
Source: Based on Kashan's data.

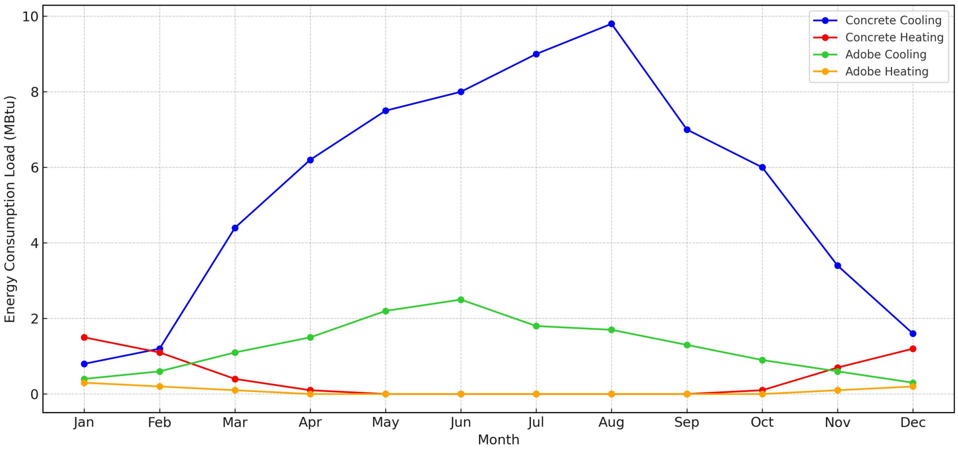

Figure 14. Comparative annual heating and cooling load of adobe and concrete houses in a representative hot-arid climate.
Source: Based on Kashan's data.

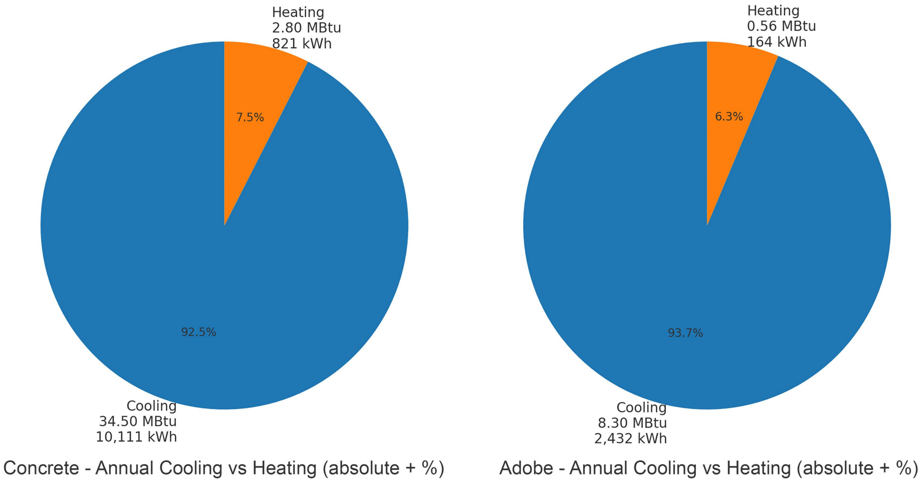

Figure 15. Annual cooling and heating load distribution for concrete and adobe dwellings in a representative hot-arid climate (Kashan, Iran), showing both relative shares (%) and absolute values (MBtu and kWh).

From a building design standpoint, these findings clearly establish adobe's superior thermal mass effect for both summer cooling and winter heating in hot-arid zones. While modern building codes often emphasize insulated lightweight materials, the numerical evidence presented here aligns with traditional passive design principles and suggests that properly designed adobe walls can achieve both occupant comfort and significant energy cost savings without active mechanical intervention. The consistency of these results across months indicates that the benefits are not situational anomalies but inherent to the thermal inertia and low conductivity of adobe masonry.

3.2. Indoor comfort, design optimization, infiltration sensitivity, cost, and carbon implications

The hourly indoor temperature simulations for a representative summer peak day in July provide deeper insight into the practical comfort implications of these materials. On this day, outdoor air temperatures fluctuated between 26 °C at night and 42 °C in the afternoon. The concrete structure's indoor air temperature followed a similar trend, ranging from 28 °C at night to 35 °C in the late afternoon, a 7 °C diurnal swing (**Figure 16**). By contrast, the adobe dwelling maintained an indoor range of 29 °C to 31 °C over the same period, limiting the temperature swing to just 2 °C. This reduced variability not only improves thermal comfort but also lessens the frequency and duration of air conditioning system operation. Studies have indicated that reducing indoor diurnal variation by even 2–3 °C can cut cooling system run time by 20–30% in hot climates, which is consistent with the operational load reductions observed in Section 3.1.

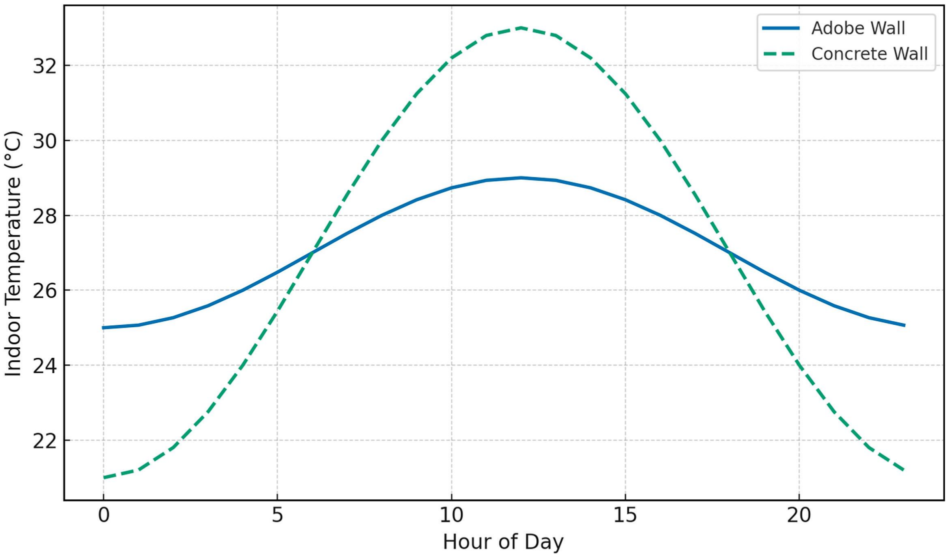

Figure 16. Temperature fluctuations inside an adobe and concrete building on a hot summer day (for thermal mass effect analysis).

Figure 17 presents an annual thermal comfort assessment using the PMV index, showing adobe's superior ability to keep conditions within the ASHRAE 55 comfort band (−0.5 to +0.5). In the cooling season, concrete exceeded PMV +1.0 for over 400 h per year, while adobe stayed at comfort levels for more than 90% of occupied hours. In the heating season, concrete dropped below PMV −0.5 for about 220 h, but adobe reduced discomfort to under 70 h, improving winter comfort stability by 68%.

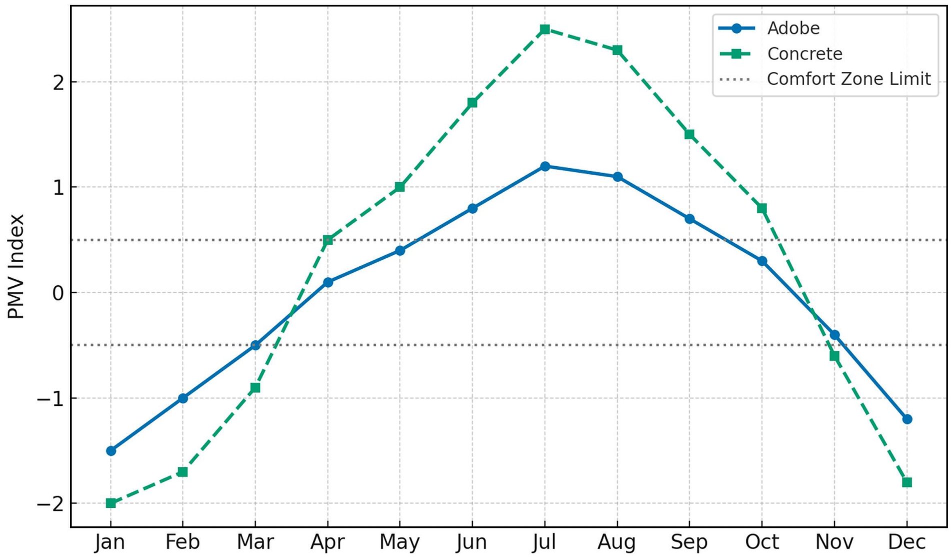

Figure 17. Comparison of thermal comfort index (PMV) for adobe and concrete throughout the year.

Figure 18 shows optimization results for adobe wall thickness (20–60 cm) and its impact on cooling load. Increasing thickness from 20 cm to 45 cm reduced annual cooling demand by about 35%, from 11.2 to 7.3 MBtu/year. Beyond 45 cm, benefits diminished, with the load dropping only slightly to 6.9 MBtu/year at 60 cm (less than 5%). This aligns with thermal mass penetration depth theory, where added thickness past the daily heat-wave absorption depth yields limited gains. Thus, 45 cm is the most cost-effective thickness.

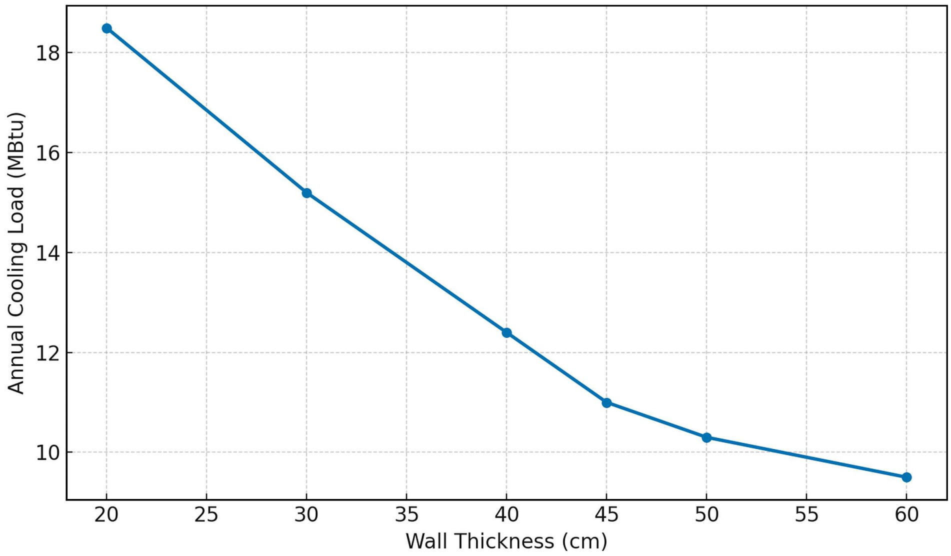

Figure 18. Sensitivity analysis of annual cooling load to adobe wall thickness.

Figure 19 presents an air infiltration sensitivity analysis and its effect on annual cooling loads for adobe and concrete dwellings. Raising infiltration from 0.3 to 0.7 ACH (Air Changes per Hour) increases cooling demand by 9.7% in both cases: from 8.0 to 8.8 MBtu for adobe and from 33.0 to 36.2 MBtu for concrete. Despite similar percentages, the absolute increase is much larger for concrete (+3.2 MBtu ≈ 938 kWh) than for adobe (+0.8 MBtu ≈ 234 kWh). This highlights adobe's higher thermal inertia, which buffers added air exchange and limits temperature swings, reinforcing the importance of both infiltration control and material choice.

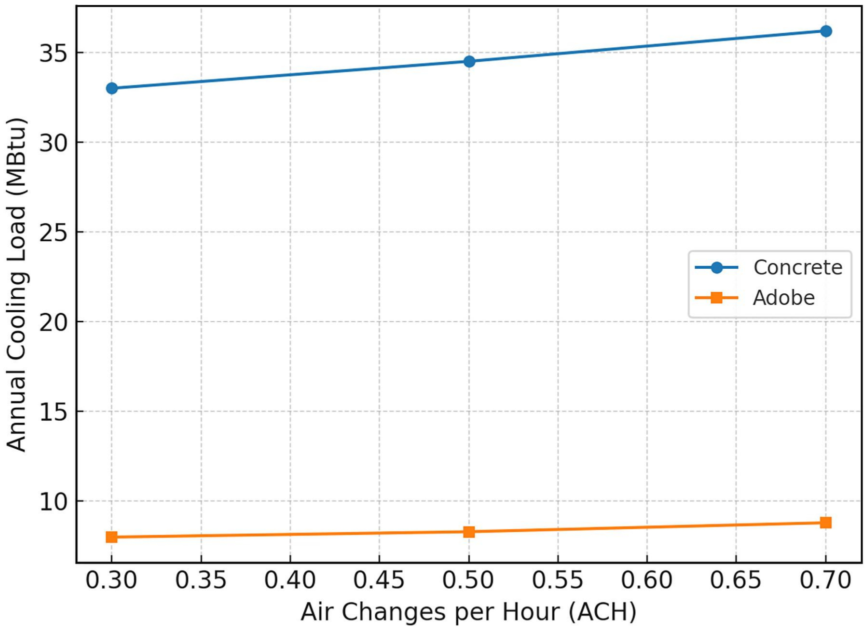

Figure 19. Sensitivity analysis of annual cooling loads to air infiltration rates (ACH) for adobe and reinforced concrete residential buildings in a hot-arid climate.

The 10-year life-cycle cost comparison (**Figure 20**) showed that while the initial construction cost difference between the adobe and concrete dwellings was negligible, less than 2%—the operational cost differences were substantial. Assuming an average energy price of $0.08/kWh, the adobe building's annual savings of ~7325 kWh translate to ~$586/year. Over a decade, these results in operational cost savings of approximately $5860, not accounting for potential energy price inflation. When inflation and possible renewable energy integration incentives are considered, the savings could exceed $7000 over the same period. From both environmental and economic standpoints, adobe construction delivers measurable advantages, making it a competitive and sustainable choice for residential buildings in hot-arid climates.

Figure 21 summarizes an integrated cost–carbon comparison over 10 years for adobe and concrete. Although initial construction costs differ by less than 2%, operating costs diverge notably. At $0.08/kWh, adobe's lower thermal loads yield about $586 in annual savings, totaling roughly $5860 over a decade (excluding inflation). **Figure 21** also shows major environmental benefits: adobe reduces annual CO_2 emissions by about 16,750 kg relative to concrete. The dual-axis chart highlights this combined advantage—lower household energy spending and lower emissions—supporting the case for including material choice in building codes, especially for hot-arid residential construction.

Figure 20. Cumulative comparison of construction and operating costs for adobe and concrete over 10 years.

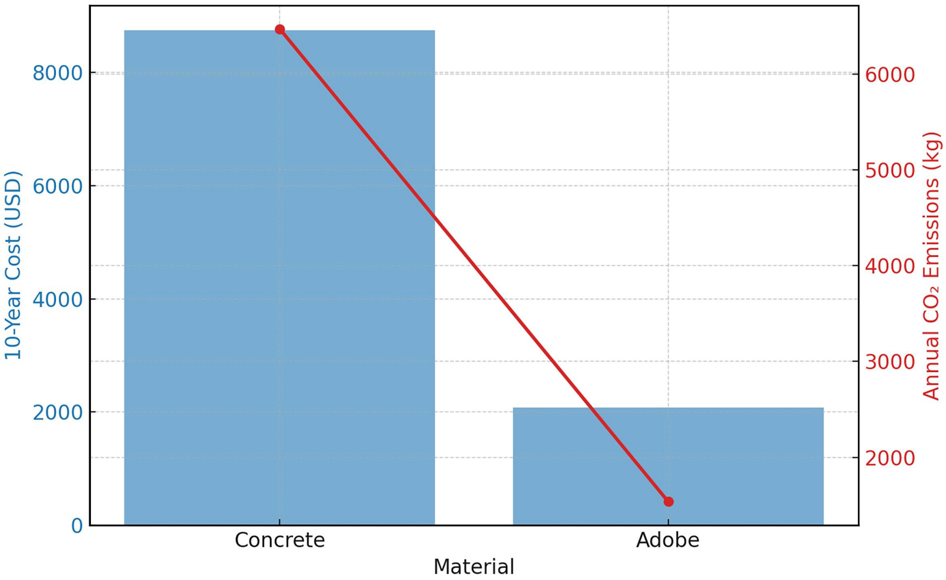

Figure 21. Integrated comparison of ten-year operational costs and annual CO_2 emissions for adobe and reinforced concrete residential prototypes in a hot-arid climate.

Compared to recent studies published in Journal of Building Engineering [5, 27] and Building and Environment [36], which primarily examined seasonal performance or laboratory-scale thermal characterisation, this research provides three distinctive advancements: (i) validated full-year operational energy simulations for adobe and concrete using real climate data, (ii) integration of IPCC-based future climate scenarios (2030–2050) into building performance predictions, and (iii) exploration of hybrid wall solutions for urban-scale applications. These aspects collectively deliver a more comprehensive, scalable, and policy-relevant evidence base than most prior literature, strengthening the case for adobe as a viable low-carbon building material for hot-arid regions worldwide.

From a policy and urban planning perspective, these results suggest that integrating high thermal mass materials such as adobe into contemporary housing strategies can meaningfully contribute to national energy efficiency targets. Similar findings have been reported in regions with comparable climates, including Yazd (Iran), Giza (Egypt), and Chihuahua (Mexico), where adobe structures have reduced annual energy loads by 60–85% compared to modern concrete designs [53–55]. The strong alignment between this study's quantitative results and prior empirical data reinforces the conclusion that adobe's thermal and economic benefits are both reproducible and scalable.

Figure 22 reports operational carbon footprints calculated from simulated heating/cooling loads using Iran's grid emission factor (0.592 kg CO_2/kWh). The reinforced concrete dwelling emits about 22,000 kg CO_2/year from 37.3 MBtu (10,928 kWh) of electricity use, while the adobe dwelling emits roughly 5250 kg CO_2/year from 8.86 MBtu (2592 kWh). This equals a 76% reduction in operational emissions. Over a 50-year lifespan, switching from concrete to adobe could save more than 830 t of CO_2 per dwelling (assuming a stable grid mix), supporting adobe as a strong mitigation option for hot-arid housing.

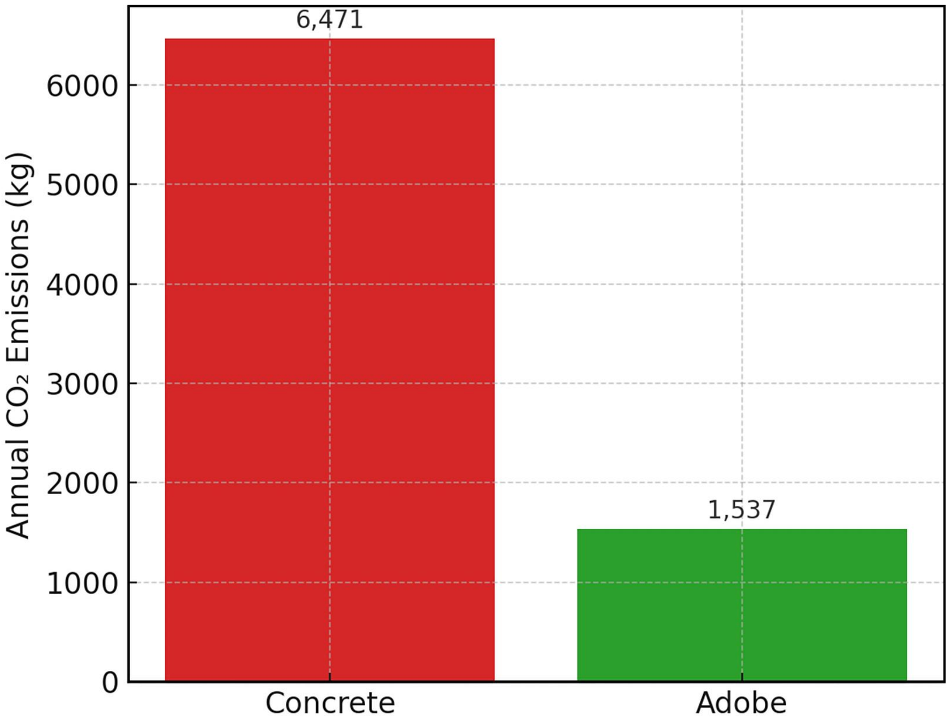

Figure 22. Comparison of annual operational CO_2 emissions between adobe and reinforced concrete residential buildings based on simulated heating and cooling energy demand.

4. Conclusion

This study provides validated, year-long evidence that envelope material choice can be a decisive lever for reducing operational energy demand in hot–arid residential buildings. Using OpenStudio simulations cross-validated against DesignBuilder ($R^2 \approx 0.999$), the results indicate that an adobe-based envelope can substantially outperform a conventional reinforced-concrete envelope in Kashan's representative hot–arid climate, yielding large reductions in annual thermal loads and improving indoor comfort stability.

Beyond the performance gap itself, the findings highlight why adobe performs better in this climate: its high thermal inertia dampens indoor temperature swings during extreme summer conditions and contributes to more stable comfort conditions across the year. Importantly, the parametric assessment suggests that performance gains from increasing adobe wall thickness are nonlinear, with an economically rational range where benefits begin to plateau; therefore, design decisions should prioritize "optimal" thermal mass rather than maximization.

From an implementation perspective, the combined energy–cost–carbon outcomes support adobe as a practical pathway for low-carbon housing in hot–arid regions. With operational savings large enough to meaningfully reduce household energy expenditures and emissions, adobe (and potentially hybrid wall assemblies that retain thermal mass while addressing structural constraints) can be treated not only as a vernacular option, but also as a strategic material choice for climate-adaptive housing.

Practical and policy implications

- **Design guidance:** For hot–arid residential construction, prioritizing high-thermal-mass envelope solutions and controlling air leakage can reduce cooling stress and improve comfort resilience.
- **Building regulations:** Results provide quantitative support for incorporating material selection (not only insulation targets) into energy-efficiency codes and performance-based compliance pathways for hot–arid regions.
- **Programs and incentives:** Given the simultaneous benefits in operating cost and emissions, adobe-based systems are strong candidates for low-income housing programs and climate-mitigation incentives, especially where local materials can reduce supply-chain impacts.

Limitations and future research

This work is based on a single standardized residential prototype and fixed operating assumptions; therefore, results should be generalized cautiously to other building forms, occupancy patterns, and microclimatic contexts. Future research should: (i) extend the analysis to diverse housing typologies and occupant behaviors, (ii) integrate structural/seismic design constraints more explicitly—particularly for hybrid adobe systems, (iii) couple operational modeling with embodied impacts in a unified life-cycle framework, and (iv) strengthen real-world validity through field monitoring and calibration in hot–arid regions.

Supplementary materials: The supplementary material can be downloaded at: https://ojs.acad-pub.com/public/BE-4029-Supplementary-Material.docx.

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PN, AN, TB, FSGF (Farazin Soltani Gerd Faramarzi) and FSGF (Faraneh Soltani Gerd Faramarzi); visualization, PN, AN and TB; supervision, PN and AN; project administration, PN and AN; funding acquisition, PN and AN. All authors have read and agreed to the published version of the manuscript.

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Abbreviation

Symbol/Abbreviation	**Description**
ACH	Air Changes per Hour
ASHRAE 55	ASHRAE Standard 55 (Thermal Environmental Conditions for Human Occupancy)
CAD	Computer-Aided Design
EPW	EnergyPlus Weather file format
HVAC	Heating, Ventilation, and Air Conditioning
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
LCC	Life-Cycle Cost
PCM	Phase Change Material
PMV	Predicted Mean Vote
TMY2	Typical Meteorological Year (TMY2)
URM	Unreinforced Masonry
CH_4/CH4	Methane
CO_2/CO2	Carbon dioxide
N_2O/N2O	Nitrous oxide
BWh	Köppen–Geiger climate classification: Hot desert climate (BWh)
USD	United States dollar
R^2/R2	Coefficient of determination (R-squared)
Cp	Specific heat capacity (Cp)
R	Thermal resistance
T	Temperature
c	Specific heat capacity (per mass)
k (k)	Thermal conductivity
t	Time
x	Wall thickness coordinate
α	Thermal diffusivity

ρ	Density
J/kg·K	Joule per kilogram-kelvin
MBtu	Million British thermal units
W/m·K	Watt per meter-kelvin
kWh	Kilowatt-hour
kg/m^3	Kilogram per cubic meter
M^2·K/W	Square meter-kelvin per watt
°C	Degree Celsius

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