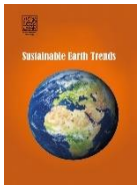
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Journal homepage: http://sustainearth.sbu.ac.ir



Planning towards zero urban energy in hot and dry climate cities in Iran; Case study: Semnan city with emphasis on solar energy

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ABSTRACT

This study aims to examine the factors influencing the reduction of fossil energy consumption and the achievement of zero-carbon urban status. The research employs a descriptive–analytical approach and, due to its emphasis on correlations among variables, is classified as correlational research. It is also applied in purpose, cross-sectional in timing, and extensive in scope. DesignBuilder software was used to calculate and analyze the energy performance of a residential building selected as the case study. The building's initial annual energy consumption was measured at 103.61 kWh/m². After implementing several carbon-reduction strategies, including enhanced insulation, optimized glazing ratios, shading improvements, and passive solar design, the consumption decreased to 56.62 kWh/m², representing a reduction of about 45 percent. Further analysis showed that integrating passive and active measures together generated greater efficiency gains than applying each measure separately. Sensitivity results indicated that envelope improvements and solar-responsive design had the strongest influence on overall energy reduction. The findings reveal that Semnan city possesses significant potential for clean-energy enhancement due to its high solar availability and climate characteristics. The study concludes that applying simulation-based evaluation alongside climate-responsive design can play a critical role in guiding Semnan toward a zero-carbon trajectory. The results also emphasize the importance of developing localized energy guidelines, encouraging efficient building technologies, and supporting urban planning policies aligned with sustainability principles. The main innovation of this research lies in presenting the first comprehensive simulation-based assessment of building energy performance in Semnan using this methodological framework.

ARTICLE INFO

Keywords:
Building energy performance
Carbon-reduction strategies
Climate-Responsive design
Energy simulation
Zero-carbon city

Article history:
Received: 16 July 2025
Accepted: 11 December 2025

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Citation:
Maghsoodi, E. et al., (2026). Planning towards zero urban energy in hot and dry climate cities in Iran; Case study: Semnan city with emphasis on solar energy, *Sustainable Earth Trends:* 6(4), (96-109).

DOI: 10.48308/set.2025.240711.1138

1. Introduction

Climate change has emerged as one of the most pressing global challenges, affecting human survival, economic growth, and environmental sustainability. Over the past decades, rising global temperatures, extreme weather events, and increasing greenhouse gas emissions have raised significant concerns about the long-term viability of current energy systems (Kaoud et al., 2024). Cities, as centers of industry, trade, and population concentration, account for approximately 70–80% of total primary energy consumption, making them critical arenas for implementing energy efficiency and low-carbon strategies (Sahu and Mahalik, 2025). Given the environmental, social, and economic impacts of climate change, transitioning urban areas toward sustainable and low-carbon energy systems is no longer optional but essential for achieving global sustainability goals. In this context, the concept of zero-energy or zero-carbon cities has gained increasing attention as a pathway to reduce greenhouse gas emissions while maintaining urban development and livability. Renewable energy sources, particularly solar energy, are well-suited to meet these objectives due to their environmental compatibility, long-term

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availability, and declining cost trends (Park et al., 2025). In addition, energy consumption is a key indicator of development and quality of life, and reducing dependency on fossil fuels while promoting renewable energy integration has become a global imperative. Considering these factors, cities with high solar potential, such as Semnan in Iran, offer unique opportunities to implement sustainable urban energy planning and serve as models for low-carbon urban development.

Extensive research has highlighted the importance of sustainable urban energy management. The integration of renewable energies and energy-efficient building design has been identified as one of the most effective strategies to mitigate environmental impacts and reduce operational costs (Alex-Oke et al., 2025). Studies demonstrate that buildings consume a significant portion of urban energy, and enhancing their energy performance can lead to substantial reductions in carbon emissions. Previous research has explored a variety of approaches, including passive solar design, advanced insulation techniques, optimized glazing, and the use of smart energy management systems. For example, studies have shown that combining multiple energy-saving measures yields greater efficiency improvements than implementing single interventions in isolation. In addition to technical solutions, urban-scale planning approaches, such as zoning for solar energy utilization and distributed renewable energy networks, have been recognized as critical components for achieving zero-energy or low-carbon urban objectives (Kaitouni et al., 2024). Despite the growing body of literature, most studies focus on either building-scale simulations or broad urban planning concepts, with limited attention to city-specific renewable energy potentials. Furthermore, previous investigations rarely consider the combination of climate-responsive architectural strategies, energy modeling, and socio-economic feasibility for specific cities, leaving a gap in the comprehensive assessment of urban renewable energy deployment. Semnan city, with its high solar irradiation levels and industrial base, provides a suitable case for integrating these approaches and examining the practical feasibility of zero-energy urban development.

Based on the identified gaps and the city's potential, the primary goal of this research is to explore the use of solar energy in Semnan's urban planning as a strategy to optimize energy consumption and advance toward a zero-energy city. The study aims to combine building-level energy modeling with broader urban planning considerations to provide a comprehensive framework for low-carbon development.

Secondary objectives include:

(a) designing near-zero-energy buildings that leverage renewable energy sources and climate-responsive design principles,

(b) proposing practical urban planning strategies to enhance energy efficiency and reduce greenhouse gas emissions, and

(c) assessing the feasibility of scaling building-level interventions to the city scale while maintaining economic and environmental sustainability. By addressing these objectives, the study seeks to provide actionable recommendations for urban managers, engineers, and policymakers to institutionalize sustainable energy practices and enhance Semnan's role as a model for renewable-energy–driven urban development.

The novelty of this research lies in its integrated approach, which combines simulation-based evaluation of building energy performance, climate-responsive design solutions, and urban-scale renewable energy planning within a single framework for Semnan city. Unlike previous studies that focused exclusively on either technical building interventions or general urban energy policies, this study bridges the gap between micro- and macro-level energy strategies, offering a holistic roadmap toward zero-energy urban development. Furthermore, the research provides a localized assessment that considers Semnan's unique climatic conditions, solar potential, and industrial context, enabling the development of tailored, evidence-based solutions. The study also contributes to the broader scientific discourse by demonstrating the practical application of zero-energy concepts in mid-sized cities of developing countries, where resource constraints and rapid urbanization pose distinct challenges. In conclusion, by evaluating the feasibility of solar-based energy optimization and proposing actionable urban planning strategies, this research establishes a foundational framework for Semnan to transition toward a sustainable, zero-energy future, while offering insights and methodologies that can be applied to similar cities worldwide.

Sustainability has become a central global priority since the 1970s as concerns over environmental degradation, resource depletion, and climate change intensified. The building sector alone consumes nearly half of the world's energy resources, one-sixth of global water supplies, and two-fifths of manufactured materials, while generating approximately half of all greenhouse gas emissions (Talbot et al., 2025). With global construction projected to double within the next four decades, the need for sustainable approaches in the built environment is more urgent than ever. Consequently, sustainable building design which emphasizes efficient resource use, reduced pollution, and environmentally conscious material selection plays a critical role in mitigating global warming and ensuring long-term ecological balance (Cellura et al., 2024).

Extensive research highlights renewable energy as one of the most effective pathways toward reducing fossil fuel dependency, improving energy security, and lowering atmospheric pollutants (Yeo, 2023; Zeddies et al., 2025). Solar, wind, biomass, and hydropower systems have been widely adopted in many regions, with global electricity generation from renewables reaching nearly 28% in 2020 due to accelerated installation of solar and wind systems (Gaurav et al., 2025). Many countries including China, the United States, and the European Union have significantly increased their investments in renewable technologies as part of broader strategies for sustainable development and emission reduction. Meanwhile, research on zero-energy and green buildings demonstrates that advanced materials, smart control systems, and renewable energy integration can dramatically reduce urban carbon footprints and help cities transition toward net-zero futures (Majrouhi, 2019; Zhao et al., 2025).

Given the accelerating global transition toward renewable energies and low-carbon urban development, the present study aims to investigate the feasibility of achieving zero-urban-energy conditions in hot and dry regions of Iran, with a specific focus on Semnan city. The research seeks to: (1) evaluate the potential of solar energy as a primary renewable source for urban energy supply; (2) assess architectural and technological strategies for reducing building energy consumption; and (3) identify planning approaches that support the integration of renewable energy systems into the urban fabric of hot and dry climate cities.

A review of the existing literature reveals two major research gaps: first, the absence of studies addressing zero-urban-energy planning in Iran's hot and dry regions, and second, the lack of research emphasizing solar-based urban energy strategies specifically for cities such as Semnan. While global scholarship has thoroughly examined zero-energy buildings, climate impacts, and renewable integration, no study has explored these issues within the unique climatic, geographic, and socio-economic context of Iranian desert cities. Therefore, the novelty of the present research lies in its localized assessment of zero-urban-energy potential and its development of a solar-centered framework tailored to hot and dry regions. By addressing these gaps, this study contributes new insights for urban planners, policymakers, and energy engineers seeking sustainable, climate-responsive strategies for future urban development in Iran.

2. Material and methods

The present study is applied in terms of practical objectives and is classified as a cross-sectional study with respect to time. Considering its analytical breadth, it is also categorized as extensive research. From a methodological standpoint, the research follows a mixed-method approach, combining quantitative building-energy simulation with qualitative revision of sustainability indicators based on local bioclimatic characteristics.

2.1. Data collection

To perform the quantitative analysis, a comprehensive dataset related to the physical, operational, and climatic characteristics of a representative residential building in Semnan was collected. The data obtained can be categorized into three groups:

1. Building Physical and Architectural Data:

- Geometrical characteristics (total floor area, floor height, building footprint, number of stories).
- Envelope specifications (wall materials, roof structure, glazing type, insulation levels, thermal transmittance/U-values).
- Window-to-wall ratio, shading devices, and building orientation.

These data were gathered from architectural plans, construction documents, and field observations.

2. Mechanical, Electrical, and Operational Data:

-Specifications of heating and cooling systems (system type, COP/EER, capacity, distribution system details)

-Ventilation rates and infiltration levels

-Lighting systems and internal heat gains from occupants and appliances

-Operational schedules (occupancy profile, equipment uses, thermostat set-points)

These data were obtained from building technical sheets, interviews with facility managers, and standard residential operation schedules relevant to Semnan climate.

3. Climatic and environmental data:

-Hourly climate data for Semnan (temperature, humidity, solar radiation, wind speed and direction)

-Bioclimatic characteristics relevant to energy performance

This dataset was collected from the official Semnan meteorological database and integrated into the simulation weather file.

4. Energy modeling and analysis procedure:

Quantitative analysis was conducted using DesignBuilder a simulation platform based on the EnergyPlus engine. The analytical process involved the following steps:

- Model Construction: Building geometry and envelope properties were input into DesignBuilder according to the collected architectural and physical data.

- System Definition: HVAC systems, lighting, schedules, and internal loads were defined to reflect the actual operating profile of the selected building.

-Baseline Simulation: A baseline energy model was simulated to estimate annual energy consumption for heating, cooling, lighting, equipment loads, and ventilation.

-Scenario Analysis: Multiple energy-efficiency scenarios were tested by altering variables such as:

-Insulation thickness

-Glazing type

-HVAC system efficiency

Shading strategies

Results were compared to evaluate the sensitivity of each parameter to total building energy consumption.

5. Result extraction and interpretation:

Outputs including monthly and annual energy use intensity (EUI), peak loads, and subsystem energy breakdown were analyzed statistically to determine patterns of inefficiency and potential improvements.

6. Qualitative analysis and indicator adaptation:

Alongside the quantitative simulations, the study conducted a qualitative assessment based on the global LEED rating system. The following steps were undertaken:

- Extraction of LEED Indicators

Relevant sustainability criteria were identified from the LEED framework.

-Localization Process

Indicators were reviewed and reclassified using qualitative methods (expert interviews, comparative document analysis, and contextual evaluation). The aim was to adapt the global standard to the biological, cultural, and climatic characteristics of Semnan.

-Integration of Simulation Results

Findings from the energy simulations were used to prioritize indicators with the highest impact on building performance under Semnan's climatic conditions.

2.2. Study area

Semnan is one of the cities of Iran, the capital of Semnan Province and Semnan County. This city is located in the south of the Alborz Mountains and the north of the desert plain on the way to Tehran from Khorasan. Semnan City, covering an area of 11,017 square kilometers, is situated on the southern slopes of the Alborz Mountains.

General slope of the city: 1 to 3 percent.

General slope direction of the city: southeast.

In general, the climate of Semnan City is in the dry and semi-arid and hot group and has 325 sunny days per year. Semnan is influenced by the hot and dry air currents of the desert plain, and its distance from the sea and the direction of the mountains and the wind also affect the city's climate.

-Average annual precipitation: 140.8 mm.

-The highest average in July (31.5 degrees Celsius) and the lowest in January (4 degrees Celsius.

Table 1. Three basic pillars of green city planning (zero carbon) and the relationship between these three factors (Source: Chen et al., 2025).

Urban planning and transportation	Water and biodiversity	Energy and materials
-Urban design -Social sustainability -Ecological urban theory -Mobility and public transport -Infrastructure -Energy-efficient buildings -Mixed land use -Housing prices -Reducing car dependency	-Urban water management -Water cycle and irrigation -Urban agriculture -Urban landscape typology -Biodiversity enhancement - Ecosystem -Wastewater cycle -Urban stormwater storage -Urban impact management -Climate change impact management -Waste management	-Energy Capture -Material Properties -Supply Chain -Sustainable Energy Solutions =Building Systems -Prefabrication and Recycling =Energy Efficiency =Recycling

Table 1 presents the three fundamental pillars of green city planning aimed at achieving zero-carbon urban development: Energy and Materials, Water and Biodiversity, and Urban Planning and Transportation. The first pillar emphasizes the efficient use and management of energy and construction materials, including energy capture, sustainable building systems, prefabrication, recycling, and overall energy efficiency. The second pillar focuses on water resources and ecological considerations, covering urban water management, the water cycle, wastewater treatment, urban agriculture, biodiversity enhancement, and strategies for mitigating the impacts of climate change. The third pillar addresses the design and organization of urban areas, promoting social sustainability, ecological urban theories, energy-efficient infrastructure, mixed land use, public transportation, and reducing car dependency. These three pillars are interrelated; for example, efficient energy use in buildings supports low-carbon urban transport systems, while urban planning decisions influence water management and biodiversity conservation. Together, they provide a holistic framework for designing cities that minimize environmental impact while enhancing livability and resilience. By integrating these pillars, urban planners can create synergies between resource efficiency, ecosystem health, and sustainable mobility, ultimately moving toward a zero-carbon urban future.

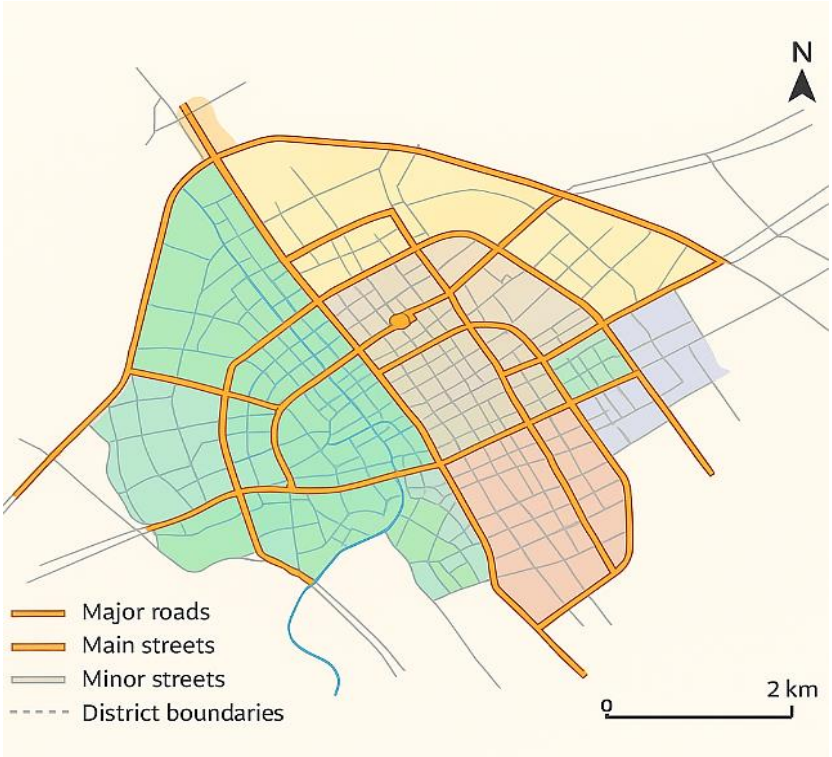


Fig. 1. Urban geographic features of Semnan city.

Fig. 1 provides a detailed representation of the street network of the city, showing both main and secondary roads. The northern and central parts of the city display the highest density of streets, suggesting that these areas likely host the main residential, commercial, and administrative zones. The thicker lines on the Fig. 1 indicate the major arterial roads, which serve as the primary routes for traffic flow and urban connectivity. In contrast, the southern and peripheral areas of the city appear less dense, which may correspond to industrial zones, agricultural lands, or open spaces. Overall, Fig. 1 illustrates the hierarchical structure of the city's transportation network and highlights the spatial distribution of urban development.

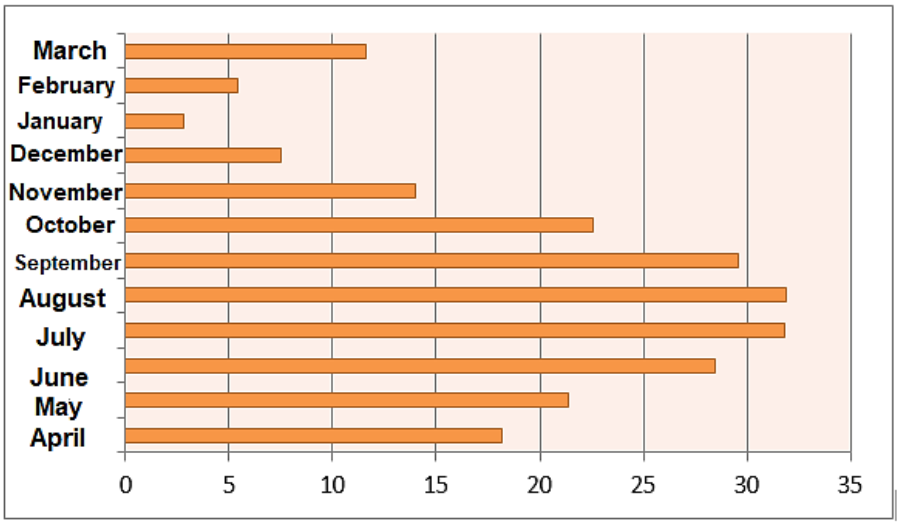


Fig. 2. Average monthly temperature of Semnan city in degrees Celsius, based on the 2021 Statistical Yearbook (Source: Ehteshamfar et al., 2024).

Fig. 2 illustrates the average monthly temperatures in Semnan city, measured in degrees Celsius, based on data from the 2021 Statistical Yearbook. The Fig. 2 highlights the region's pronounced seasonal variations, with peak temperatures occurring in the summer months and the lowest values in winter. These temperature patterns are critical for understanding building energy demand, as they directly influence heating and cooling loads throughout the year. For instance, high summer temperatures increase cooling requirements, while cold winters drive higher heating energy consumption. Analyzing this data allows architects and urban planners to design climate-responsive buildings and implement energy efficiency strategies tailored to Semnan's local conditions. Ultimately, these temperature trends provide a foundational reference for modeling building energy performance and informing sustainable urban planning decisions.

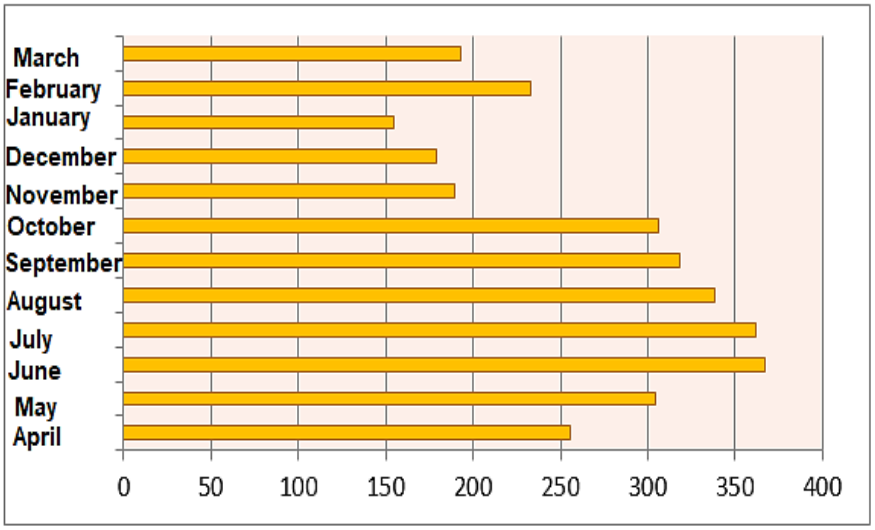


Fig. 3. Sunshine hours in Semnan city, source: Statistical Yearbook 2021 (Source: Ehteshamfar et al., 2024).

Fig. 3 presents the average monthly sunshine hours in Semnan city, based on the 2021 Statistical Yearbook. The data highlights periods of high solar exposure, particularly during late spring and summer, which are critical for optimizing solar energy utilization in buildings. Understanding the distribution of sunshine hours allows designers to maximize natural daylight, reduce reliance on artificial lighting, and plan for solar energy systems such as photovoltaic panels or solar water heaters. Additionally, this information supports climate-responsive building design, including shading strategies and building orientation, to improve thermal comfort and energy efficiency. Integrating sunshine data into urban planning can also inform broader sustainability strategies, contributing to the development of low-carbon or zero-energy neighborhoods. Overall, these insights are essential for aligning building performance with Semnan's local climatic conditions.

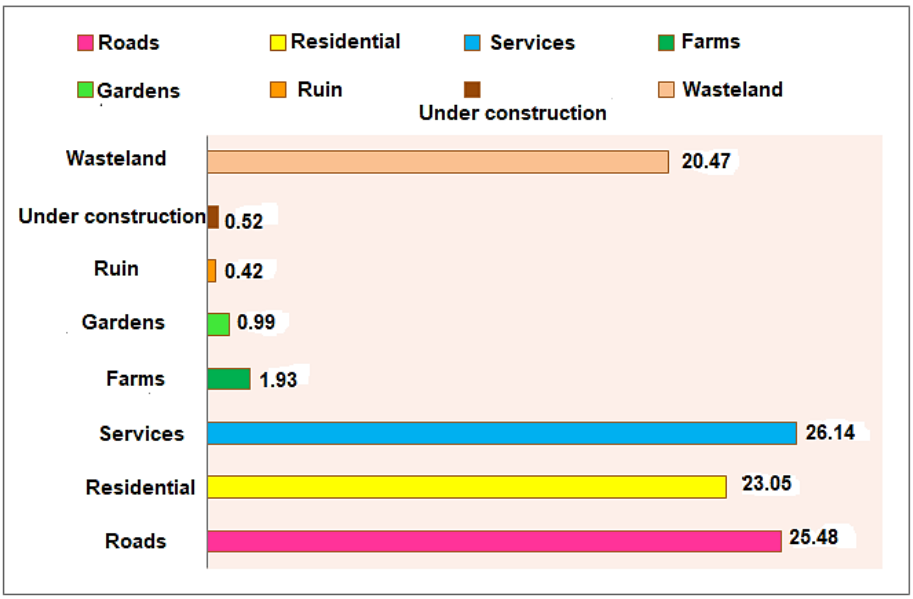


Fig. 4. Percentage of land use in Semnan city, source: Statistical Yearbook 2021 (Source: Ehteshamfar et al., 2024).

Fig. 4 illustrates the percentage distribution of land use in Semnan city, based on the 2021 Statistical Yearbook. The Fig. 4 highlights how urban, residential, commercial, industrial, and green spaces are allocated across the city, providing a clear picture of the current spatial organization. Understanding land use patterns is crucial for sustainable urban planning, as it affects transportation networks, energy consumption, and access to green areas. For example, higher proportions of residential and commercial areas can increase energy demand and traffic, while the presence of green spaces supports biodiversity, urban cooling, and stormwater management. This information enables planners to identify opportunities for mixed-use development, improved public transport access, and low-carbon urban strategies. Overall, land use analysis serves as a key foundation for designing efficient, resilient, and sustainable urban environments in Semnan.

3. Results and discussion

In the present study, a residential building is selected as a representative sample, and all the parameters influencing the building's energy performance are systematically analyzed. The evaluation and results are obtained through simulations using Design Builder software, which allows for precise modeling of energy flows and environmental conditions. The study aims to investigate how each parameter contributes to the reduction of energy consumption during both hot and cold seasons, as well as to determine the cooling and heating loads of the building critical factors in designing a zero-energy building. A detailed analysis is conducted on a single-story residential building designed for a single household. The total area of the building is approximately 260 square meters, efficiently divided among the various parts of the home. The building includes three bedrooms of suitable size for family members, a spacious

living room that serves as the main area for daily family activities and gatherings, a kitchen featuring a standard layout with sufficient space for cooking and storage, and one combined bathroom and toilet shared by the occupants. The overall layout of the house is typically designed to allow ample natural light to enter through properly oriented windows. Convenient access between rooms and common areas is also ensured. Depending on the architectural design, an outdoor yard or green space may be included, contributing to improved quality of life for the residents. The construction materials commonly used for such buildings include brick or block walls, a joist-and-block or composite roof structure, and ceramic or stone flooring.

Overall, this building represents a standard residential unit suitable for a family with typical daily needs, offering functional interior organization and spatial distribution that align with a conventional lifestyle. Meteorological data relevant to the location are incorporated using the EnergyPlus simulation engine, which provides detailed weather information for accurate modeling. In addition, various construction and design parameters, such as insulation levels, window types, orientation, and building materials, are examined to understand their impact on energy demand. Lighting, ventilation, and occupancy patterns are also considered to provide a comprehensive assessment of the building's annual energy performance. Finally, this section presents the calculation of the building's total annual energy consumption, highlighting the most influential factors and offering insights into strategies for optimizing energy efficiency in residential buildings.

Table 2. Calculation of the primary energy of the selected building.

Energy	MJ	Unit of consumption	Cubic meter	Number of days
365	19	37.68	72644	Gas
365	150		24333	Electricity
A=	260	m^2		
E actual=			372.99	MJ/m^2
Equivalent			103.61	$kwh/year/m^2$

The data in Table 2 provide a detailed calculation of the primary energy consumption of the selected residential building. The table indicates that natural gas consumption accounts for 72,644 cubic meters annually, with a corresponding energy content of 37.68 MJ per unit, resulting in a total energy usage of 19 MJ over 365 days. Electricity consumption is reported as 24,333 kWh per year, contributing an additional 150 MJ per unit over the same period. When normalized by the building's area of 260 m², the actual energy consumption is calculated as 372.99 MJ/m² per year, equivalent to 103.61 kWh/m²/year. These figures highlight the dominant contribution of gas to the building's total primary energy demand, indicating that heating or hot water loads are likely the largest components of energy use. Electricity, while a smaller portion of the total energy, still represents a significant share and includes consumption from lighting, appliances, and other electrical systems. The conversion of total energy into per-unit area allows for comparison with energy efficiency standards and benchmarks, providing a clear understanding of the building's energy performance. Overall, the results emphasize the importance of optimizing both gas and electricity usage to reduce overall primary energy consumption and improve the sustainability of residential buildings. According to the above relationship and the calculation made, the annual energy consumption in the building in question is equal to 103.61 kWh/m^2 per year, which is a huge distance from the desired energy level and zero-energy buildings.

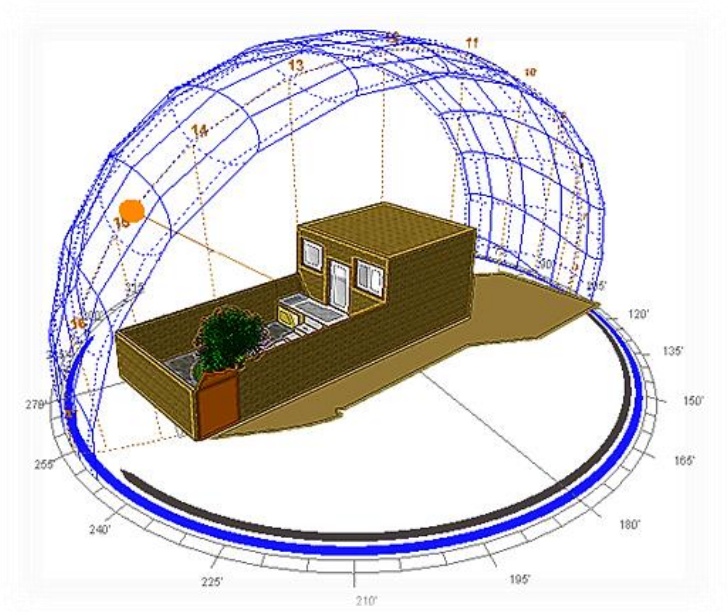


Fig. 5. Simulation of the studied building in Design Builder software and its output (Source: Research findings).

Modeling details using designbuilder: The building's energy performance was evaluated using the DesignBuilder simulation software, which incorporates the EnergyPlus calculation engine (Fig. 5). In the first stage, a detailed digital model of the single-story residential building was created, including its architectural layout, construction materials, occupancy patterns, and local climate conditions.

Key elements defined in the model included:

Geometric modeling of the 260 m² single-story structure, including the three bedrooms, living room, kitchen, and bathroom;

Construction properties, such as wall layers, roof composition, floor materials, glazing type, and thermal transmittance (U-values) based on locally used building standards;

Internal loads and schedules, covering occupancy density, lighting power, appliance usage, and domestic hot water consumption;

HVAC system specifications, including the type of heating and cooling systems, equipment performance levels, and control strategies;

Climate data, imported using the local EPW weather file to accurately represent annual temperature and solar radiation patterns;

Ventilation and infiltration rates, modeled according to standard residential building assumptions or measured values where applicable.

After defining all parameters, an annual energy simulation was performed. The initial results showed that the building's total energy consumption amounted to 103.61 kWh/m² per year.

In the second phase, several carbon-reduction strategies were incorporated into the model. Depending on the case, these strategies may have included:

Improved thermal insulation for walls and roofs;

High-performance glazing;

Enhanced air-tightness and reduced infiltration;

Upgraded HVAC system with higher efficiency;

Installation of shading devices;

Optimization of lighting systems or use of daylighting controls

Once these measures were added, the simulation was run again under identical conditions. The results demonstrated a significant reduction in energy use, with the building's consumption decreasing to 56.62 kWh/m² per year.

This comparative modeling process highlights how targeted design strategies can substantially enhance building energy performance and reduce operational carbon emissions.

This image shows a daylighting simulation and sun path analysis for a building. A few important points about it:

The building structure is designed in a simple rectangular shape and includes elements such as windows and a small green space in front of the house.

The blue arc around the building represents the sun's path across the sky during the day or year

and is typically used for analyzing natural light and solar radiation.
The circle marked on the sun path indicates the sun's position at a specific time, which can be useful for examining shadows and direct sunlight.
These types of simulations help architects and designers optimize building daylighting, reduce energy consumption, and ensure adequate interior lighting.
Definition of solar angles:
In sunlight modeling, usually two main angles are considered:
a. Solar Elevation / Altitude Angle
-The angle between the imaginary horizon line and the position of the sun in the sky.
-When the sun is directly overhead, the angle is 90 degrees.
-This angle determines how directly sunlight strikes the ground or the building.
b. Solar Azimuth Angle
-The horizontal angle between the north direction and the sun's position on the horizon.
-It specifies from which side of the building the sunlight is coming.
Calculation of the sun's position:
The sun's position is usually determined using astronomical formulas or solar tables:
ϕ=latitude of the locationδ=solar declination (depends on date and month), H=hour angle (determines the time of day).
ϕ=latitude of the locationδ=solar declination (depends on date and month), H=hour angle (determines the time of day).
These calculations tell the software at what angle the sun is relative to the building at any given moment.
Calculation of shadows:
Knowing the sun's altitude and azimuth angles, the length and direction of shadows on the ground or building can be calculated (Eq. 1):

$$\text{Shadow length} = \frac{\text{Object height}}{\tan(\text{Altitude angle})} \quad (1)$$

-If the altitude angle is low (sun near the horizon), the shadow is long.
-If the altitude angle is high (sun overhead), the shadow is short.
-The direction of the shadow is determined based on the sun's azimuth angle.
Application in building design:
-Ensuring that windows and openings receive maximum daylight.
-Reducing the need for artificial lighting and energy consumption.
-Analyzing direct sunlight on interior spaces during summer and winter (temperature control).
-Determining the optimal building orientation relative to the sun's path.
Overall, this simulation shows that the designed building effectively utilizes natural light, and its openings are oriented toward the main path of the sun. The sun's trajectory and angle of incidence indicate that shadows fall optimally on the building and the front green space at different times of the day. Using this model helps maintain appropriate interior daylighting throughout the year and reduces the need for artificial lighting. By analyzing the solar altitude and azimuth angles, the effect of direct sunlight on walls and windows can be predicted, allowing interior temperature control. In summary, this simulation is a valuable tool for sustainable design and enhancing the building's energy efficiency.
In the next step, the impact of various factors on the building's energy consumption is examined to minimize the building's energy consumption. Measures such as double-glazed windows, the use of solar panels, etc.

Table 3. Energy calculation of the selected building after applying the solutions (Source: Research findings).

Energy	MJ	Cubic meter	Unit of consumption	Number of days
Gas	38234	37.68	10	365
Electricity	14762		91	365
		260	m^2	=A
MJ/m^2	203.83			=E actual
$kwh/year/m^2$	56.62			Equivalent

Table 3 presents the energy performance of the selected residential building after applying various energy-saving solutions, based on the research findings. The annual gas consumption is reduced to 38,234 cubic meters, with an energy content of 37.68 MJ per unit, while electricity consumption is lowered to 14,762 kWh per year. Normalizing these values by the building's area of 260 m² results in an actual energy consumption of 203.83 MJ/m² per year, equivalent to 56.62 kWh/m²/year. This represents a substantial reduction compared to

the initial values reported in Table 2, highlighting the effectiveness of the applied solutions. The significant decrease in gas consumption indicates that heating and hot water systems have been optimized, likely through improved insulation, better building envelope design, or more efficient HVAC systems. Similarly, the reduction in electricity usage suggests that lighting, appliances, and other electrical systems have been upgraded to more energy-efficient models or better managed through behavioral and automated control strategies. This comprehensive improvement in energy performance demonstrates the building's transition toward a low-energy or nearly zero-energy status.

Furthermore, the normalized energy values (per square meter) provide a clear metric for comparing this building with other residential buildings and international energy efficiency standards. The results emphasize that both passive measures (such as orientation, insulation, and natural ventilation) and active solutions (efficient heating, cooling, and lighting systems) are necessary to achieve meaningful reductions in energy consumption. Overall, Table 3 confirms that a combination of well-planned design interventions and technical upgrades can reduce operational energy demand by approximately 45–50%, thereby lowering costs, reducing greenhouse gas emissions, and enhancing the building's sustainability.

4. Conclusion

In recent decades, with the increase in the world population and concerns about the significant rise in the consumption of conventional fuels, the need for sustainable and reliable access to energy has become more apparent than ever. Fossil fuels are non-renewable energy sources that will be depleted in the not-so-distant future. These energy sources pose global challenges such as environmental pollution and greenhouse gas emissions. Given the possibility of serious energy imbalances in the coming years, relying on renewable energies seems essential to overcome these limitations and shortcomings. The use of renewable energies in the current world has received considerable attention and has expanded rapidly. Moreover, the growing urgency of climate change has motivated countries to accelerate their transition toward cleaner energy systems. Technological advances have also enhanced the feasibility and cost-effectiveness of renewable alternatives, making them more attractive for large-scale deployment. At the same time, many governments and international organizations have adopted policies and incentives to support clean energy development, reflecting a global shift toward sustainability. As a result, the integration of renewable energy sources has become a central component of long-term energy planning worldwide. Based on this, the aim of the authors in this study was to examine the factors influencing the reduction of fossil energy consumption and the achievement of zero-carbon urban status in Semnan city. The initial simulation results showed that the annual energy consumption of the examined building was 103.61 kWh/m². By applying a set of carbon-reduction strategies including improved insulation, optimization of glazing ratios, enhancement of shading elements, and passive solar design the energy consumption decreased to 56.62 kWh/m², representing a reduction of about 45 percent. This significant decrease indicates that even relatively simple but targeted interventions in building design can play a substantial role in improving energy efficiency. In particular, optimizing materials and envelope details minimized heat loss in cold seasons and reduced heat gain during hot seasons, thereby lowering the need for mechanical heating and cooling systems. Additional analyses further revealed that combining passive and active strategies simultaneously offers greater effectiveness compared to implementing each measure individually, as the synergy between these approaches considerably enhances the overall performance of the building. Sensitivity results also showed that envelope improvements and sun-responsive design had the strongest impact on total energy reduction, underscoring the critical importance of climate-responsive design in hot and dry regions.

This study demonstrated that applying a set of building design strategies and energy optimization measures can result in a significant reduction in energy consumption and carbon emissions. The initial simulation results indicated that the building's annual energy consumption was 103.61 kWh/m². By implementing carbon-reduction strategies, including improved insulation, optimization of window-to-wall ratios, enhancement of shading

elements, and passive solar design, energy consumption decreased to 56.62 kWh/m², representing an approximate 45% reduction. This substantial decrease highlights the crucial role of targeted interventions in building design for improving energy efficiency.

A more detailed analysis revealed that combining active and passive strategies was more effective than implementing each measure individually, as the interaction between these approaches significantly enhanced overall building performance. In particular, improvements to the building envelope and solar-responsive design had the greatest impact on energy reduction, underscoring the importance of climate-responsive design in hot and dry regions. Additionally, the use of appropriate building materials and optimized exterior design minimized heat loss in winter and reduced heat gain in summer, thereby lowering the demand for mechanical heating and cooling systems.

Furthermore, the results indicated that precise simulations and climatic data analysis can predict the optimal building design path and prevent costly implementation errors. Semnan, with its high solar radiation, hot and dry climate, and substantial solar energy potential, provides an ideal environment for utilizing solar panels, passive design strategies, and modern energy management systems. Ultimately, the combination of simulation-based analysis and climate-responsive design serves as a powerful tool for achieving zero-carbon urban objectives and provides guidance for policymakers and urban planners to implement sustainable energy solutions at a broader scale.

The findings of this study are consistent with the results reported by Kaitouni et al. (2025), Zhao et al. (2025), and Gondal (2024), indicating that passive design and optimization of building envelope and details play a significant role in reducing energy consumption and enhancing efficiency. These studies also reported notable reductions in energy use through window optimization, insulation improvements, and the use of shading devices, aligning closely with the results of the present research. Specifically, the importance of climate-responsive design, the combination of active and passive strategies, and the impact of the building envelope on energy performance have been emphasized in similar studies.

However, the results of this study show less alignment with those reported by Hosseinzadeh (2022), Taher Ahmadi et al. (2023), and Rezaeinasab et al. (2023). This discrepancy may be attributed to differences in climate conditions, local contexts, building types, or simulation methodologies. For instance, the buildings examined in this study are located in a hot and dry climate with higher solar radiation and distinct thermal conditions compared to other regions, which affects the effectiveness of passive strategies and envelope designs differently.

While the core analysis of this study focuses on a single residential building, the findings provide insights with meaningful implications at the city scale. Many buildings in Semnan share similar structural and operational characteristics, suggesting that the identified efficiency measures could be replicated widely. If applied across comparable building types, the cumulative reduction in energy demand could form a substantial share of the city's overall consumption and support broader zero-energy urban strategies. These results highlight how micro-scale improvements can guide macro-level planning decisions, particularly in shaping building codes, retrofit programs, and energy-efficient urban policies. Ultimately, the study demonstrates that enhancing the performance of individual buildings can serve as a foundational step toward advancing Semnan's transition to a low-carbon, and eventually zero-carbon, future.

Additionally, the findings indicated that combining active and passive strategies simultaneously is more effective than implementing them separately, a factor that has been less comprehensively analyzed in previous studies. This research provides a comprehensive, simulation-based framework for evaluating building energy performance in Semnan and establishes a foundation for future studies on low-energy building design and energy policy development. Therefore, this study can serve as a practical and scientific reference for other hot and dry cities in the country, enhancing climate-responsive design strategies and energy efficiency at an urban scale.

Finally, according to the results and findings of the research and in order to achieve a zero-carbon city, the following suggestions are noteworthy for Semnan:

- ✓ Double-glazed glass in buildings along with sealing and reducing penetration;
- ✓ Use of double-skin facades;
- ✓ Orientation of buildings towards the benefit from favorable light and wind;
- ✓ Creating a height difference on the roof in the direction of the sun's movement for shading at different times of the day Increasing the height of the building in order to reduce or suddenly increase the temperature;
- ✓ Using appropriate sunshades to prevent light from entering in the summer Maximum use of renewable and desert-like building materials and minimum use of building materials with a concentration of non-renewable energy, such as steel, brick, vinyl, aluminum, and insulation;
- ✓ Looking back and avoiding unnecessary things to increase efficiency and save costs;
- ✓ Attracting private sector investment in the development and modernization of the public transportation fleet and refueling stations can be done by doing the following:

Providing financial and tax facilities: The government It can provide financial and tax facilities to private investors in this industry. These facilities include tax breaks, low-interest loans, and credit facilities.

Covering the exterior of the building: With green space and appropriate vegetation to adjust the temperature and reduce temperature fluctuations Using a garden and a water pond for evaporative cooling.

Research Limitations:

- ➢ Climatic Data Limitations: The simulation was based on available climatic data, and high-resolution long-term datasets were not fully accessible, which may affect the precision of the results.
- ➢ Limited Building Sample: The study focused on a single building in Semnan, limiting the generalizability of the findings to other buildings or urban contexts.
- ➢ Incomplete Simulation of Active Systems: Not all mechanical and electrical systems of the building were fully simulated, which could influence the overall energy consumption outcomes.
- ➢ Economic Evaluation Constraints: A comprehensive cost-benefit or economic analysis of implementing the proposed measures was not conducted, and the study primarily focused on technical and energy-related impacts.

Recommendations for future research:

- ❖ Expand Study to Diverse Buildings: Conduct studies on a variety of building types and scales in Semnan to enhance the generalizability of findings and assess design strategies across different structures.
- ❖ Comprehensive Economic Analysis: Integrate full cost-benefit evaluations to assess the financial feasibility, payback periods, and potential economic incentives for implementing energy-saving measures.
- ❖ Urban-Scale Integration: Combine energy simulation with urban sustainability modeling to evaluate the collective impact of passive and active design strategies on city-wide energy performance and carbon reduction.
- ❖ Advanced Renewable and Smart Technologies: Investigate the integration of novel renewable energy technologies and intelligent energy management systems in residential and commercial buildings to further reduce dependency on fossil fuels and improve efficiency.

Acknowledgment

This article was not under any financial support.

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