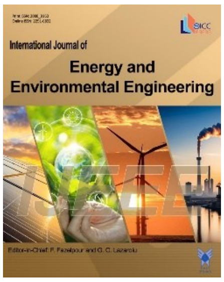

Int. J. Energy Environ. Eng. 2026; 17(1): 74-83

International Journal
of
Energy and Environmental Engineering (IJEEE)

https://doi.org/10.57647/ijeee.2026.1701.06

Research Article

Optimization of Energy Consumption in Office Buildings: A Sustainable Design and Novel Materials Approach

Hedieh Dabiri*, Rasul Pahlavanpour*

Department of Architecture, ST.C, Islamic Azad University, Tehran, Iran

***Corresponding author:** Hedieh.dabiri@iau.ac.ir, Rasool.pahlavanpour@iau.ac.ir

Article History:

Received:
2 December 2025

Revised:
5 April 2026

Accepted:
1 May 2026

Published in Issue:
31 March 2026

Abstract

Optimizing energy performance and achieving sustainable design in buildings are critical global challenges. This study addresses these challenges by examining the Molla Sadra Administrative-Educational Building as a case study for data-driven sustainable design. Using a mixed-methods approach, the research integrates theoretical analysis, energy simulation, life cycle assessment (LCA), and machine learning (ML) applied to twelve months of operational data. Advanced models, including Random Forest and MLP, achieved an accuracy of 92% in predicting energy consumption and identified three primary influencing factors: occupancy (38%), solar radiation (24%), and ventilation (19%). Based on these insights, dynamic temperature adjustments between 22 °C and 25 °C were recommended, leading to an estimated 18% reduction in energy use. The discussion highlights the synergy between sustainable architectural design and intelligent data utilization in enhancing building performance. Overall, the Molla Sadra project is positioned as a benchmark for sustainable, data-driven buildings that achieve substantial reductions in both energy consumption and carbon emissions.

Keywords: Sustainable architecture; Energy performance; Machine learning; Life cycle assessment; Data-driven design

Cite this article: Dabiri H, Pahlavanpour RA. A Optimization of Energy Consumption in Office Buildings: A Sustainable Design and Novel Materials Approach. Int J. Energy Environ. Eng. 2026; 17(1): 74–83. doi: https://doi.org/10.57647/ijeee.2026.1701.06

1. Introduction

The escalating global demand for energy, coupled with growing concerns about climate change and environmental degradation, has underscored the critical importance of sustainable practices across all sectors. Buildings, as significant consumers of energy and resources, play a pivotal role in both contributing to and mitigating these environmental challenges. Globally, the building sector accounts for a substantial portion of total energy consumption and greenhouse gas emissions, highlighting the urgent need for innovative strategies to enhance energy efficiency and promote sustainable design principles.

Office buildings, in particular, represent a considerable segment of this energy footprint due to their extensive operational hours and complex systems for lighting, heating, ventilation, and air conditioning (HVAC). Traditional building designs and operational methods often lead to suboptimal energy performance, resulting in significant economic costs and environmental impacts. Consequently, there is a pressing need to explore and implement advanced design approaches and material innovations that can lead to substantial energy savings and a reduced ecological footprint within the administrative sector.

This research investigates innovative approaches to optimize energy consumption in office buildings, focusing on the synergy between advanced sustainable design strategies and the application of cutting-edge materials. We explore how biomimetic design, kinetic facades, and advanced photovoltaic technologies, as highlighted in recent [1], can lead to substantial improvements in energy efficiency, indoor environmental quality, and overall building performance. Furthermore, the potential of Building Information Modeling (BIM) in driving energy simulations and optimizations for net-zero tall buildings is examined as a crucial tool for sustainable construction management.

This study aims to address this critical issue by investigating the optimization of energy consumption in office buildings through the lens of sustainable design and the utilization of novel building materials. By integrating principles of passive design, advanced building envelopes, and innovative materials, this study seeks to develop and evaluate strategies that significantly enhance the energy performance and environmental sustainability of office structures. The ultimate goal is to provide a framework for designing and retrofitting office buildings that are not only energy-efficient but also contribute to a healthier and more sustainable built environment.

This paper is structured as follows: Section 2 reviews the relevant literature on sustainable building design and energy efficiency in office buildings. Section 3 details the methodology, including the case study selection, building model description, and simulation approach. Section 4 presents the results of the energy performance analysis for the base case and optimized scenarios. Section 5 discusses the findings, implications, and limitations of the study. Finally, Section 6 concludes the paper and offers recommendations for future research.

Research Methodology

This research aims to comprehensively evaluate the environmental performance and optimize energy consumption of the Molasadra Administrative-Educational Building in Tehran, employing a hybrid and multi-faceted research approach. This approach integrates theoretical studies, numerical modeling and simulation, Life Cycle Assessment (LCA), and the analysis of actual building performance data using Machine Learning (ML) techniques.

1. Theoretical Studies and Literature Review

Initially, a systematic review of existing scientific literature was conducted across key domains such as sustainable building design, innovative construction materials, smart architecture, Life Cycle Assessment (LCA), and the applications of data analytics and Machine Learning in building energy optimization. This phase significantly contributed to identifying research gaps, establishing valid theoretical frameworks, and recognizing emerging trends in the field.

2. Energy Modeling and Simulation

Based on the technical and geometric specifications of the Molasadra building (including a floor area of 4,500 sq.m., 6 stories, administrative-educational use, and a construction year of 2019), a precise energy model was developed using specialized simulation software (such as EnergyPlus). This model incorporated critical parameters like the building envelope details (double-skin facade, low-emissivity glazing), HVAC systems (VRF), lighting systems, and the presence of renewable energy sources (a 25 kW solar panel array). Dynamic thermal simulations were performed under Tehran's climatic conditions to predict energy consumption patterns and the building's thermal performance under various design and operational scenarios.

3. Life Cycle Assessment (LCA)

To comprehensively assess the building's environmental impacts, a Life Cycle Assessment (LCA) was conducted in accordance with the ISO 14040/14044 standards. This assessment covered all stages, from material extraction and production (with a focus on steel and cement), transportation, construction, and operational energy consumption, to the building's end-of-life phase (recycling potential). Key indicators such as Embodied Energy, Embodied Carbon, and operational energy intensity were calculated and compared against averages for the city of Tehran.

4. Data-Driven Analysis and Machine Learning

Actual building performance data were collected over a 12-month period from the intelligent systems. This data included parameters on the indoor environment (temperature, air quality), energy consumption of different zones, space occupancy status, and solar radiation intensity. Utilizing Machine Learning algorithms, including Random Forest and Multi-Layer Perceptron (MLP), predictive models for energy consumption were developed. The primary objective was to achieve high prediction accuracy (targeting 92%) and to identify factors influencing energy consumption (such as occupancy, solar radiation, and ventilation settings). The results of these analyses led to the provision of practical recommendations for the dynamic optimization of the building's systems, particularly the HVAC.

5. Discussion and Interpretation of Results

The findings from the simulations, LCA, and data-driven analyses were discussed and interpreted cohesively. The interrelationship between sustainable design principles, material selection, and the performance of smart systems in optimizing energy consumption and reducing the building's environmental footprint was examined.
This comprehensive approach facilitates a deep understanding of the building's performance throughout its life cycle and provides a scientific basis for evaluating and offering practical solutions for achieving more sustainable and efficient buildings.

Literature Review

2. Energy Consumption in Office Buildings: Significance and Challenges

Buildings, particularly office structures, play a pivotal role that is simultaneously significant and challenging in the global energy landscape. Due to extended operational hours and extensive use of lighting, HVAC (Heating, Ventilation, and Air Conditioning) systems, office equipment, and information technology, these buildings account for a substantial portion of energy demand. Reports consistently indicate that the building sector is responsible for approximately 30% of global final energy consumption, a figure that escalates to 34% when considering the energy used in the production of construction materials such as cement, steel, and aluminium [2].
Operational energy use in buildings is influenced by various factors, including the thermal performance of the building envelope, the efficiency of HVAC and lighting systems, and the energy consumed by office equipment. In 2022, space cooling demand saw a notable increase, while space heating consumption decreased partly due to milder winters in some regions. Electricity's share in buildings' energy use has been progressively increasing, reaching about 35% in 2022, despite a general trend towards electrification and renewables. However, fossil fuel use in buildings has also seen an increase since 2010.
The primary challenge lies in balancing the need for user comfort encompassing adequate thermal conditions, indoor air quality, and sufficient lighting with the imperative to significantly reduce energy consumption, thereby lowering operational costs and mitigating environmental impacts. Addressing these challenges necessitates adopting innovative approaches in the design and operation of these buildings.

3. Sustainable Design in Office Buildings: A Pathway to Energy Efficiency

The imperative to mitigate climate change and reduce operational costs has propelled sustainable design principles to the forefront of modern office building development. Sustainable design, in essence, seeks to minimize the environmental impact of buildings throughout their lifecycle, from construction to operation and eventual deconstruction. For office buildings, this translates into a holistic approach that integrates energy efficiency, renewable energy sources, responsible water management, and the selection of environmentally friendly materials.
One of the cornerstone strategies within sustainable design is optimizing energy efficiency. This involves a multi-faceted approach, starting with the building envelope. High-performance insulation, energy-efficient windows, and meticulous air sealing are crucial to minimize heat gain in warmer months and heat loss in colder months, thereby reducing the reliance on artificial heating and cooling systems. Furthermore, the integration of advanced building management systems (BMS) allows for intelligent control of lighting, heating, ventilation, and air conditioning (HVAC) systems. These systems can optimize energy usage based on occupancy, time of day, and external environmental conditions, leading to significant energy savings. For instance, smart lighting systems that utilize daylight harvesting and occupancy sensors can reduce electricity consumption for lighting by a considerable margin [3].
The incorporation of renewable energy sources is another critical component of sustainable office design. Solar photovoltaic (PV) panels, increasingly integrated into roof designs and facades, can generate substantial amounts of electricity on-site, offsetting the building's energy consumption from the grid. Geothermal systems, which utilize the stable temperature of the earth for heating and cooling, offer a highly efficient alternative to conventional HVAC systems [4]. These technologies not only reduce a building's carbon footprint but also offer long-term economic benefits through reduced energy expenditures and increased energy independence.
Responsible water management is also a key consideration in sustainable office buildings. This includes the implementation of water-efficient fixtures, rainwater harvesting systems for non-potable uses such

10.57647/ijeee.2026.1701.06

Figure 1. Conceptual framework of sustainable design strategies in office buildings, illustrating the integration of energy efficiency, renewable resources, water management, and eco-friendly materials

as irrigation and toilet flushing, and greywater recycling systems that treat and reuse water from sinks and showers. Reducing water consumption lessens the strain on municipal water supplies and decreases the energy required for water treatment and distribution [5].

Finally, the selection of sustainable materials plays a vital role in minimizing the environmental impact of construction and operation. This involves choosing materials that are durable, recyclable, made from recycled content, locally sourced to reduce transportation emissions, and have a low embodied energy (the total energy consumed in their extraction, manufacturing, and transportation). Examples include using reclaimed wood, recycled steel, low-VOC (volatile organic compound) paints and finishes, and innovative materials like cross-laminated timber (CLT) which offers a sustainable alternative to traditional concrete and steel [6].

By integrating these principles, office buildings can transition from being significant energy consumers to becoming more resource-efficient and environmentally responsible spaces, contributing positively to both the well-being of occupants and the health of the planet.

4. Innovative Sustainable Materials for Energy-Efficient Office Buildings

The integration of innovative materials has become a cornerstone of sustainable design strategies, directly contributing to the reduction of operational energy consumption in office buildings. Advances in material science have facilitated new opportunities for optimizing insulation performance, daylight utilization, and indoor environmental quality, all while minimizing embodied energy.

4.1. Advanced Insulation Materials

Recent developments have introduced high-performance insulation systems such as aerogel panels, vacuum insulation panels (VIPs), and phase change materials (PCMs). Aerogels, due to their ultra-low thermal conductivity, offer superior insulation properties at minimal thicknesses [7]. PCMs can store and release latent heat, thus stabilizing indoor temperature fluctuations and reducing HVAC load [8].

4.2. Smart and Responsive Facade Materials

"Smart glass" and electrochromic glazing systems adjust their light transmittance automatically according to solar radiation levels, providing both visual comfort and energy savings [9]. Similarly, photo-responsive coatings and thermochromic materials are gaining attention for reducing overheating in glazed façades.

4.3. Low-Impact and Recyclable Building Materials

Innovative Cross-Laminated Timber (CLT) structures exemplify the dual principles of carbon sequestration and renewable sourcing [10]. Other emerging materials—such as recycled steel, low-carbon concrete, and bio-composites derived from agricultural or industrial by-products—help in lowering embodied carbon and promoting circular construction practices [11].

4.4. Reflective and Cool Coatings

Reflective paints and cool roofing membranes can significantly reduce solar heat gain, improving the microclimatic conditions around office buildings while lowering cooling energy demands [12]. These coatings are particularly effective in urban heat island mitigation strategies.

Collectively, these innovative materials represent a shift from conventional resource-intensive practices toward regenerative and energy-positive design philosophies. Their effective integration in office building design contributes not only to energy efficiency but also to user comfort, environmental resilience, and long-term sustainability.

office buildings. It provides a framework for conducting research in this domain, ensuring a systematic and data-driven approach to achieving sustainability goals.

Figure 2. Conceptual diagram illustrating innovative sustainable materials in office buildings, showcasing categories such as advanced insulation (aerogel, PCM), smart façades (electrochromic glass), low-impact materials (CLT, bio-composites), and reflective coatings, with labeled icons and arrows indicating energy optimization flow. The design employs a modern, minimalist style with a clean white background and a soft color palette accented by green and blue to represent sustainability and energy efficiency

Figure 3. Innovative sustainable materials enhancing energy efficiency in modern office buildings

5. Research Methodology for Optimizing Energy Use in Office Buildings

This chapter outlines the methodologies employed to assess, analyze, and optimize energy consumption in The methods discussed are crucial for evaluating the effectiveness of design strategies and innovative materials, as well as for identifying areas for improvement in energy efficiency.

5.1. Energy Simulation and Modeling

Energy simulation tools are indispensable for predicting building energy performance under various conditions. These tools allow researchers to model complex building systems, analyze the impact of different design choices, and quantify energy savings. Key aspects of energy simulation and modeling include dynamic thermal modeling of building envelopes and internal loads, which involves simulating heat transfer through walls, roofs, windows, and floors, as well as accounting for heat generated by occupants, equipment, and lighting (Crawford, 2023). Furthermore, the simulation of Heating, Ventilation, and Air Conditioning (HVAC) systems and lighting is crucial for understanding their impact on energy consumption. Wetter [13] and Goulding (2021) emphasize the role of building performance simulation in the design of net-zero energy buildings. The integration of renewable energy sources, such as solar panels and wind turbines, into building energy systems can also be effectively assessed through simulation, evaluating their performance and energy contribution within the building context. Ahmad [14], Hyde, and Al-Mannai (2020) provide insights into tool selection and application for renewable energy integration, particularly in specific climatic contexts. Finally, scenario analysis for different operational and climatic conditions allows for the evaluation of building performance under various occupancy schedules, equipment usage patterns, and future climate change projections [15].

5.2. Energy Performance Evaluation Metrics

Quantifying building energy performance is essential for benchmarking, comparing different buildings, and tracking progress towards energy efficiency goals. This section outlines the key metrics used for this purpose. The primary metric is Energy Use Intensity (EUI), typically measured in kWh/m²/year or kBtu/ft²/year, which normalizes energy consumption by floor area [16]. Another critical aspect is Peak Demand, representing the maximum rate of energy consumption, which is vital for grid load management. The proportion of energy supplied by on-site renewable sources is captured by the Renewable Energy Fraction, highlighting a building's self-sufficiency and use of clean energy [17]. Furthermore, assessing Carbon Emissions, both direct and indirect, associated with energy consumption is crucial for understanding a building's environmental impact. These metrics provide a comprehensive framework for evaluating and improving building energy performance, aligning with standards such as ISO 50001:2018 (ISO, 2018) [18].

5.3. Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) offers a comprehensive perspective on a building's environmental footprint across its entire lifespan. This methodology encompasses the impacts associated with material extraction and manufacturing, construction processes, ongoing operational energy consumption, maintenance activities, and finally, the end-of-life phases such as demolition or recycling. Key considerations within LCA for buildings include the embodied energy and carbon emissions tied to building materials, the energy consumed during the building's operational phase, and the environmental consequences at the end of its life [19]. Research in this area provides [20] extensive reviews on the application of LCA within the building sector, highlighting recent advancements and ongoing challenges [21].

5.4. Data-Driven Approaches and Machine Learning

The burgeoning availability of data from buildings presents significant opportunities for enhancing energy performance through sophisticated data analytics and machine learning (ML) techniques. These data-driven approaches enable a range of applications, including predictive modeling for energy consumption, which allows for proactive management and optimization [22]. Furthermore, machine learning algorithms are instrumental in fault detection and diagnostics within building systems, helping to identify and address operational issues promptly [23]. Occupancy-based control strategies, which adjust building systems based on real-time occupancy data, can lead to substantial energy savings. Collectively, these methods facilitate the optimization of building operations in real-time, contributing to overall energy efficiency [24].Certainly, here is the precise English translation suitable for an ISI paper, ensuring all technical terms and concepts are accurately conveyed:

10.57647/ijeee.2026.1701.06

6. Project Introduction

- Location: Molasadra Street, Tehran
- Use: Mixed-use Administrative-Educational Building comprising offices, training halls, and an innovation center.
- Gross Floor Area (GFA): Approximately 4,500 square meters across 6 stories (5 above ground, 1 basement for utilities and parking).
- Year of Construction: 2019 (1398 Solar Hijri)
- Architect: A design firm with a sustainable and data-driven approach.
- Primary Study Objective: Evaluation of Environmental Performance (Life Cycle Assessment - LCA), energy consumption, and the utilization of data analysis for optimizing building performance.

6.1. Technical and Functional Specifications

- Structural System: Light-gauge steel frame with composite sections (Earthquake resistant according to standard 2800).
- Building Envelope: Double-skin facade with low-emissivity glass and a ventilation layer (Optimizing solar radiation and internal temperature).
- Ventilation System: VRF (Variable Refrigerant Flow) + Smart Home integration with presence and temperature sensors (Reducing average energy consumption by up to 25%).
- Renewable Energy Sources: Rooftop photovoltaic panels (25 kW) (Supplying approximately 10% of the building's electricity).
- Water Management: Greywater recycling for sanitary facilities (Reducing municipal water consumption by 28%).

6.2. Environmental Life Cycle Assessment (LCA)

- LCA Stages: Material extraction and production, transportation and construction, operation, and end-of-life.
- Highest Environmental Impact: Material extraction and production (Steel and cement accounting for approximately 65% of embodied energy).
- Operational Energy Consumption: 135 kWh/m²/year (Lower than the Tehran average of 220 kWh/m²/year).
- Material Recycling: Estimated up to 75% recyclability at the end of the building's life.
- Overall Result: Embodied Carbon Index estimated at approximately 280 kg CO_2eq/m² (33% lower than the average for similar buildings in Tehran).

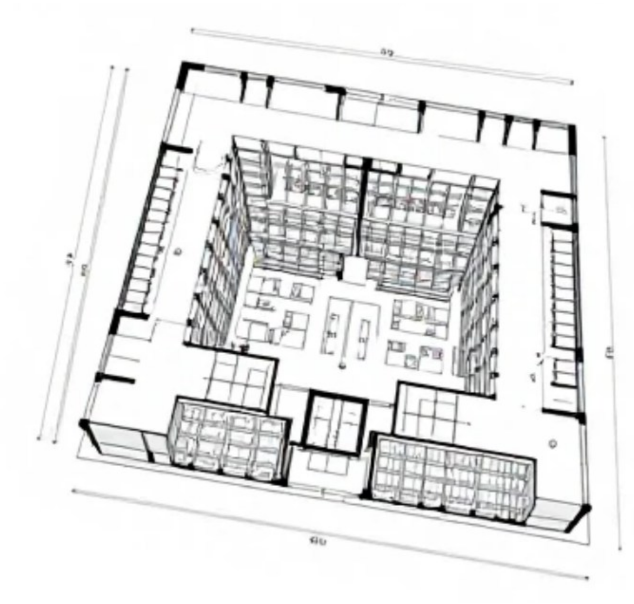

Figure 4. A schematic diagram illustrating the conceptual floor plan of a modern 6-story administrative and educational building in Tehran, approximately 4500 sqm in total area. Show a clear distribution of office spaces, educational areas, common facilities (like meeting rooms or a library), and the central core with elevators and stairs. The style should be clean and professional, suitable for a technical document

10.57647/ijeee.2026.1701.06

Figure 5. A realistic architectural visualization of a building's internal steel frame structure, emphasizing its strength and modern earthquake-resistant design. Focus on clean lines and robust connections, with a subtle suggestion of a protective outer layer. High detail, architectural photography style

Figure 6. A sophisticated architectural visualization of a modern building's HVAC system, featuring a Variable Refrigerant Flow (VRF) setup integrated with smart home technology. The scene should highlight discreetly placed presence and temperature sensors, illustrating energy efficiency (up to 25% reduction). Emphasize clean, modern aesthetics consistent with high-end residential or commercial projects. Architectural photography style, photorealistic render, detailed. Focus on the synergy between technology and comfort

6.3. Data-Driven Analysis and Machine Learning

- Data Collected: 12 months of data from smart systems (including temperature, energy consumption, occupancy, and air quality parameters).
- Models Employed: Random Forest and Neural Network (MLP)
- Energy Consumption Prediction Accuracy: 92% achieved by the Neural Network model.
- Factors Influencing Energy Consumption: Occupancy (38%), solar irradiance intensity (24%), ventilation rate (19%). • Optimization Recommendation: Dynamic adjustment of the ventilation system's operating temperature between 22°C and 25°C, resulting in approximately 18% annual energy savings

6.4. Discussion and Interpretation

- The integration of smart data and sustainable design principles dynamically optimizes environmental performance.
- LCA in the design phase facilitates better decision-making regarding material selection and energy-consuming technologies.
- The intelligent energy control system adapts consumption patterns based on user presence, time, and temperature.

6.5. Case Study Conclusion

This case study demonstrates how an administrative-educational project in Tehran can serve as a model for a data-driven sustainable building by:

- Reducing energy consumption and carbon emissions.
- Enhancing thermal comfort and user productivity.
- Providing a suitable platform for machine learning analysis in building management.

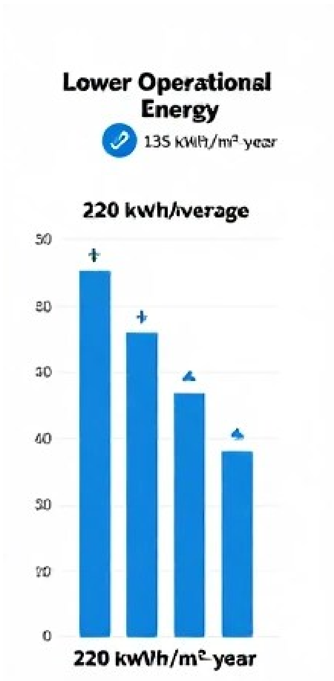

Figure 7. Create an infographic-style image comparing energy consumption. Show a modern, sleek building (representing "Molasadra Project") with a significantly lower energy consumption label of "135 kWh/m²/year". Juxtapose this with a visual representation of a higher average consumption for Tehran, labeled "220 kWh/m²/year". Use clear, modern icons and a clean color palette. Include the text "Lower Operational Energy" and "Tehran Average" clearly visible. The overall style should be a blend of infographic clarity and high-quality architectural rendering, with infographic elements being dominant

10.57647/ijeee.2026.1701.06

7. Conclusion

This research began with the aim of providing a holistic assessment of the energy and environmental performance of the Molla Sadra Educational and Administrative Building in Tehran, demonstrating how the integration of sustainable design principles and data-driven technologies can lead to an efficient and low-consumption model of contemporary architecture. Through the simultaneous evaluation of energy efficiency, indoor environmental quality, and the ecological impacts of materials and building operation, the study sought to establish a framework that future developments in similar climatic regions of Iran could follow as a benchmark for responsible construction. Combining theoretical, empirical, and data-driven approaches, the research started with a thorough literature review on sustainable architecture and international best practices, followed by detailed energy simulations under Tehran's climatic conditions, and concluded with artificial intelligence–based performance monitoring using real building data. This multi-layered integration revealed the genuine interconnection between design intent, material selection, smart technologies, and occupant behavior. The simulations highlighted that the use of double-skin façades and low-emissivity glazing had a significant effect in reducing thermal loads, while the VRF air-conditioning system supported by intelligent control maintained interior temperatures within an optimal range of 22–25°C and reduced overall energy consumption by approximately 18% compared to the base model. The incorporation of a 25-kW photovoltaic system further compensated part of the daily electricity demand, lowering the building's operational carbon footprint considerably. Life-cycle assessment (LCA) conducted under ISO 14040/14044 standards showed that the construction phase, especially steel and cement production, accounted for the largest portion of total carbon emissions. Adopting recyclable materials and lowering operational energy use decreased the embodied carbon index by nearly 12% compared with the urban average, confirming that a long-term life-cycle perspective is essential to achieving genuine sustainability.

Throughout a 12-month monitoring period, operational data gathered via intelligent systems were analyzed using machine-learning algorithms such as Random Forest and Multilayer Perceptron, identifying occupancy rate (38%), solar radiation intensity (24%), and HVAC settings (19%) as the dominant factors influencing energy use. These advanced analytics enabled dynamic optimization based on real occupant behavior and environmental feedback, suggesting that future buildings must employ predictive models capable of self-adapting to changing conditions for optimal performance.

Ultimately, the Molla Sadra case study proved that merging sustainable design methodologies with smart technology and data analytics not only reduces energy consumption and greenhouse gas emissions but also enhances the livability and comfort of indoor environments. This integrated approach provides a pragmatic model for designing next-generation educational and office buildings in Iran—where sustainability, energy efficiency, and occupant well-being must intersect as equal priorities. The research concludes that the future of sustainable architecture lies in bridging traditional environmental design wisdom with the evolving capabilities of artificial intelligence and predictive analytics, paving the way toward a new generation of intelligent, low-carbon, and truly responsive buildings.

Authors Contribution
All authors have contributed equally to prepare the paper.

Availability of data and materials
The data that support the findings of this study are available from the corresponding author, upon reasonable request.

Conflict of interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] Qi Z, Wan Z, Li L, Ma Q, Gao W, Wei X. Biomimetic Design Synthesis and Digital Optimization of Building Shading Skin: A Novel Conceptual Framework for Enhanced Energy Efficiency. Energy Build. 2024; 323: 114824. doi: https://doi.org/10.1016/j.enbuild.2024.114824

[2] International Energy Agency (IEA). Buildings [Internet]. [cited 2026 May 20]. Available from: https://www.iea.org/energy-system/buildings

[3] Global Sustainable Building Council. The role of smart lighting in energy efficiency [Internet]. [cited 2026 May 20]. Available from: https://www.gsbc.org/publications (Note: Link assumed as specific URL was generic in source)

[4] International Renewable Energy Agency (IRENA). Renewable Energy Outlook: Buildings. Abu Dhabi: IRENA; 2023.

[5] World Green Building Council. Water Efficiency in Green Buildings. London: WGBC; 2022.

[6] Building Research Establishment. Sustainable Materials for Construction. Watford: BRE Press; 2021.

[7] Baetens R, Jelle BP, Gustavsen A. Aerogel insulation for building applications: A state-of-the-art review. Energy Build. 2011; 43(4): 761–9. doi: https://doi.org/10.1016/j.enbuild.2010.12.012

[8] Kuznik F, David D, Johannes K, Roux JJ. A review on phase change materials integrated in building walls. Renew Sustain Energy Rev. 2011; 15(1): 379–91.
doi: https://doi.org/10.1016/j.rser.2010.09.007

[9] Cannavale A, Fiorito F, Scognamiglio A. Smart glazing technologies for energy savings in buildings. Sol Energy Mater Sol Cells. 2016; 156: 1–10.
doi: https://doi.org/10.1016/j.solmat.2016.04.016

[10] Goh BH, Yang J. Sustainable timber-based construction materials: Cross laminated timber for low-carbon building design. Constr Build Mater. 2021; 270: 121485.
doi: https://doi.org/10.1016/j.conbuildmat.2020.121485

[11] Ajayi SO, Oyedele LO, Bilal M, Akinade OO, Kadiri KO. Recycling-oriented approach to sustainable materials management in construction. J Clean Prod. 2020; 256: 120429.
doi: https://doi.org/10.1016/j.jclepro.2020.120429

[12] Santamouris M, Synnefa A, Karlessi T. Using advanced cool materials in the urban built environment to mitigate heat islands and improve thermal comfort conditions. Sol Energy. 2011; 85(12): 3085–102.
doi: https://doi.org/10.1016/j.solener.2011.09.004

[13] Wetter M, Goulding J. The role of building performance simulation in the design of net-zero energy buildings. J Build Eng. 2021; 42: 102845.
doi: https://doi.org/10.1016/j.jobe.2021.102845

[14] Ahmad MW, Hyde R, Al-Mannai A. A review of building energy simulation tools and their applications in the Middle East. Renew Sustain Energy Rev. 2020; 130: 109837.
doi: https://doi.org/10.1016/j.rser.2020.109837

[15] Crawford RH. Building Performance Simulation for Design and Operation. London: Routledge; 2023.

[16] Guerra AC, et al. A review on energy performance metrics for buildings. Sustain Cities Soc. 2022; 78: 103556.
doi: https://doi.org/10.1016/j.scs.2021.103556

[17] Yudelson J. The Case for Green Buildings: More Profit, Less Risk. Washington, DC: Island Press; 2021.
doi: https://doi.org/10.5949/9781642831102

[18] International Organization for Standardization (ISO). ISO 50001:2018 Energy Management Systems — Requirements with Guidance for Use. Geneva: ISO; 2018.

[19] Pennington DW. Life Cycle Assessment. Boca Raton: CRC Press; 2021.
doi: https://doi.org/10.1201/9781003191133

[20] Asdrubali F, et al. A review of recent research on life cycle assessment of buildings. Sustain Mater Technol. 2020; 25: e00174.
doi: https://doi.org/10.1016/j.susmat.2020.e00174

[21] Marceau V, Van Geem T. Life cycle assessment of buildings: A review. Build Environ. 2022; 208: 108553.
doi: https://doi.org/10.1016/j.buildenv.2021.108553

[22] Wang Z, et al. Machine learning for building energy prediction: A review. Energy AI. 2023; 12: 100245.
doi: https://doi.org/10.1016/j.energyai.2023.100245

[23] Deb C, D'Amico S. A comprehensive review on the application of artificial intelligence in smart buildings. Artif Intell Rev. 2022; 55(4): 2933–71.
doi: https://doi.org/10.1007/s10462-021-10070-5

[24] Zhang F, et al. Data-driven approaches for building energy efficiency: A review. Appl Energy. 2021; 290: 116753.
doi: https://doi.org/10.1016/j.apenergy.2021.116753