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RESEARCH ARTICLE

Evaluating the potential of passive design measures for energy efficiency in retrofitting an educational building towards net-zero energy goals

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Abstract

Achieving Net-Zero Energy Building (NZEB) performance requires a comprehensive approach that integrates both passive and active energy strategies. This study investigates the standalone impact of various passive design measures on reducing heating and lighting energy demands in an existing educational facility located in Safranbolu, Türkiye, a region characterized by a continental climate with mild summers and cold winters. Utilizing dynamic energy simulations conducted via DesignBuilder and the EnergyPlus engine, the research evaluates a range of envelope retrofit strategies, including optimized window-to-wall ratios (WWR), high-performance glazing systems, double-skin façades (DSFs), and advanced insulation materials. The results indicate that while passive envelope enhancements can significantly improve thermal performance, the most effective configuration identified in this case study, combining a cavity wall with aerogel insulation and triple-pane argon-filled low-emissivity glazing, achieved a 34.9% reduction in heating demand under the specific conditions of the building and climate analyzed. While passive strategies effectively reduce energy losses, they are insufficient on their own to eliminate dependence on external energy sources. To overcome this limitation, the integration of active renewable energy systems, such as photovoltaic (PV) panels and solar thermal collectors, is essential. Furthermore, incorporating energy storage technologies and smart energy management systems can enhance system reliability and efficiency. This study underscores that a hybrid approach, combining passive design with active solar technologies, offers the most viable path to NZEB achievement. Notably, the research provides an original and detailed multi-scenario evaluation of passive-only retrofit strategies, quantifying their individual and combined potential prior to the introduction of active energy systems.

1. Introduction

As global energy demand continues to rise, the building sector remains one of the largest contributors to both primary energy consumption and greenhouse gas emissions, accounting for nearly 40% of global energy use and over 30% of CO_2 emissions [1]. In response to mounting environmental pressures, the concept of Net-Zero Energy Buildings (NZEBs) has emerged as a cornerstone of sustainable building practices.

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NZEBs aim to balance annual operational energy use with on-site renewable energy generation, thereby minimizing their environmental impact and reliance on external energy sources [2]. Driven by regulatory frameworks such as the European Union's Energy Performance of Buildings Directive (EPBD), which mandates that all new buildings must be nearly zero-energy by 2030, NZEBs are becoming an increasingly important benchmark for both new construction and building retrofits [3].

While the design and performance of newly constructed NZEBs have been widely studied, the retrofit of existing buildings to NZEB standards presents a more complex challenge, especially for older structures with limited insulation, inefficient glazing systems, and suboptimal envelope design [4].

Passive design strategies, such as enhanced insulation, high-performance glazing, optimized window-to-wall ratios (WWR), and natural ventilation, are considered the most cost-effective first step in reducing building energy demand [5, 6]. These strategies utilize architectural form, material properties, and environmental conditions to enhance thermal performance while minimizing reliance on mechanical systems. However, the effectiveness of passive measures is highly dependent on local climate conditions, building use patterns, and spatial constraints, making climate-responsive design a fundamental requirement [7]. However, their effectiveness is highly dependent on climate conditions, building orientation, and material availability, making climate-responsive design a key necessity [8].

The window-to-wall ratio (WWR) is an essential design variable that significantly influences a building's energy performance, with its optimal value varying widely based on climate and building orientation [9]. Studies conducted in cold climates, such as the "severe cold area of Shenyang city" [10] shows that the most energy-efficient WWR is between 10-15% for east and west facades and 10-22.5% for southern facades. This is due to the need to balance passive solar gains with minimizing heat loss through the less insulated glazed surfaces [11]. Conversely, in hot and semi-arid climates, the primary concern is managing heat gain. A study in Tripoli, Libya [12], found that increasing the WWR generally led to higher cooling consumption. Although heating demand could decrease to zero on southern walls due to passive solar heating. Similarly, a study in Iran, characterized by a semi-arid climate [13], showed that while the lowest energy consumption was achieved with a WWR of just 5%, a much higher ratio of 45-55% was often considered optimal to balance thermal performance with essential daylighting needs. In Mediterranean climates, where both heating and cooling are relevant, research in Italy Marino et al. [14] identifies the window system as a crucial element for managing solar gains, influencing overall energy consumption. These findings are further supported by a broader analysis of US office buildings, where Troup et al. [15] found that increasing WWR is a significant predictor of increased cooling and lighting energy use. In a broader context, Arshad et al. [16] emphasized that optimizing building envelope parameters like WWR is among the critical energy retrofit strategies aligned with the Sustainable Development Goals (SDGs) for achieving Net Zero Energy Building (NZEB) targets. Similarly, Aloshan [17] identifies building envelope optimization, including façade orientation, glazing type, and WWR, as fundamental to achieving near-zero energy performance in hot climates. The literature collectively demonstrates that while the impact of WWR is not universal, its proper optimization is a fundamental first step in significantly reducing energy loads and moving a building closer to Net-Zero Energy performance.

The other crucial static window technology is Low-emissivity (Low-E) glazing, designed to improve a window's thermal and optical performance. These coatings work by reducing heat transfer through the window, thereby minimizing energy consumption [18]. The energy-saving potential of double-glazed windows is well-established and widely adopted in cold climates to reduce heating energy [19]. Conversely, in hot and humid climates, Low-E glazing is primarily used to reduce heat gain and lower the air-conditioning load [20]. The study by Somasundaram et al. [21] on a retrofit solution in Singapore found that combining a solar film with a retrofit double-glazing unit could reduce annual HVAC energy consumption by up to 20%. Another related study by Somasundaram, et al. [20] observed that installing a hard-coat Low-E double glazing unit could lead to annual energy savings of 3% for a clear glass facade and up to 7.5% for an existing tinted grey glass facade in a tropical climate with a 20% WWR. Harmati and Magyar [11] also investigated the influence of glazing properties on heating and cooling demand, emphasizing its importance in different climatic conditions. Xiaoxiang et al. [22] further highlight glazing material and light transmission as key performance indicators in NZEB retrofits across diverse climate zones, supported by bibliometric trend analyses. The literature highlights that upgrading glazing is a critical measure for a building's envelope and is a fundamental step toward achieving NZEB state [23].

Another advanced architectural strategy for improving a building's envelope performance is the use of double-skin facades (DSFs). This building technology consists of two layers of facade separated by a ventilated air gap, which can significantly improve a building's thermal and daylight performance when properly designed [24]. The performance of DSFs highly depends on climate and specific design parameters such as glazing type and cavity depth [25]. In hot arid climates, DSFs can be beneficial, with research demonstrating their ability to reduce cooling loads compared to conventional single-skin facades [26]. Similarly, in Mediterranean climates, studies show that DSFs can improve energy consumption in high-rise office buildings, with optimization of the facade being critical to achieving the desired energy performance [27]. For subtropical and temperate climates, the energy performance of DSFs has also been extensively investigated. A study on a typical office building in Hong Kong showed that, while DSFs could provide some energy benefits, their financial payback period might be long depending on the specific configuration [28]. Research conducted in Seoul confirmed that the glazing type of the inner layer significantly impacts energy consumption, highlighting the importance of a detailed, quantitative analysis in the design phase [29]. More recently, a study focusing on Turkey investigated the potential of integrating DSFs with nanotechnological materials to further enhance energy efficiency in office buildings [30]. These studies confirm that the effectiveness of DSFs is not universal and that their proper implementation requires sophisticated, climate-specific design and optimization, making them a key, albeit complex, strategy in the pursuit of a NZEB.

Moving beyond facade design, the use of advanced materials offers a complementary approach to enhancing thermal performance. Thermal insulation is one of the most effective methods for reducing a building's energy consumption where it helps lower the overall energy load from heating and air conditioning systems and meet thermal comfort needs [31]. A study by Shahee et al. [32] focuses on assessing thermal insulation and shading to optimize energy efficiency, save expenses, and foster environmental sustainability in residential buildings. The use of insulation is a fundamental first step toward achieving the high energy performance required for a NZEB. In addition to conventional insulation materials, advanced "superinsulation" materials, such as aerogels, are being developed due to their superior thermal performance and potential for significant energy savings [33, 34]. Aerogel insulating panels exhibits ultra-low thermal conductivity, making them excellent thermal insulators for building energy efficiency. Research by Cuce et al. [35] highlights that optimizing the thickness of aerogel insulation can make a significant contribution to energy savings and greenhouse gas abatement, especially in colder climates and for investments with a longer lifetime. The literature collectively demonstrates that the proper selection and optimization of insulation, including both conventional and advanced materials, is a critical component of a building's envelope design, directly influencing its energy performance and helping to achieve net-zero energy goals.

The transformation of existing buildings into NZEBs has emerged as a central focus in contemporary energy research. While a substantial body of literature has explored the design principles and operational performance of newly constructed NZEBs, comparatively limited attention has been devoted to the retrofitting of existing buildings using exclusively passive design strategies. This study seeks to address this gap by adopting a passive-only approach to NZEB retrofitting, applied to an existing educational facility. Through the use of a real-world case study and advanced simulation tools, the research evaluates the feasibility and effectiveness of passive retrofit measures in achieving significant energy performance improvements, without the integration of active mechanical or renewable energy systems. In doing so, it offers a distinct contribution to the broader discourse on sustainable retrofitting and NZEB compliance in educational building typologies.

Most NZEB research has focused on residential or office buildings, often neglecting the unique spatial, functional, and operational characteristics of educational buildings [8-36]. These facilities pose distinct energy challenges due to high occupancy densities, variable schedules, and strict daylighting requirements. Many NZEB case studies are set within temperate or Mediterranean climates [37, 38], limiting the generalizability of their findings to cold or transitional climate zones. In addition, existing studies tend to evaluate passive strategies in isolation or as part of hybrid systems that also include active renewable technologies, making it difficult to assess the standalone potential of passive retrofitting.

This research addresses these gaps by evaluating passive retrofit strategies applied to an existing higher education facility located in Safranbolu, Türkiye, a UNESCO World Heritage city characterized by a continental climate with cold winters. According to the Turkish State Meteorological Service, Safranbolu experiences average winter temperatures below 0°C, making heating demand dominant in annual energy use.

The case study building is representative of the regional building stock, with limited thermal insulation, high window-to-wall ratios, and outdated glazing systems. These features make it an ideal subject for assessing the impact of envelope-level passive interventions.

This study investigates whether passive retrofit measures alone can bring an educational building closer to NZEB performance without integrating active systems such as solar photovoltaics or mechanical HVAC upgrades. Specifically, it aims to:

- Assess the baseline energy performance (heating and lighting) of the existing building;
- Simulate and compare the effect of various passive retrofit scenarios, including:
- Quantify the energy savings potential of each measure under a heating-dominant climate condition;
- Identify the most effective passive combination strategy in terms of thermal efficiency and visual comfort.

In this study, by adopting a passive-only approach, the study aims to isolate and quantify the maximum achievable energy reduction prior to integrating active renewable systems. This also enables future cost-benefit analyses to determine the required scale and feasibility of active measures to close the NZEB performance gap.

This research contributes original insights to the field of sustainable retrofitting by:

- Providing one of the few comprehensive, scenario-based simulations of passive-only NZEB retrofits in educational buildings;
- Applying a parametric modeling approach using EnergyPlus and DesignBuilder for high-fidelity hourly energy simulations;
- Generating design guidance specific to continental climates and educational typologies, where data is currently sparse.

The findings are expected to inform architects, policymakers, and facility managers engaged in the retrofit of public educational infrastructure, particularly in climate zones where heating energy dominates and space for renewable installations may be limited.

2. Material and Method

2.1. Case study

2.1.1. Overview of the selected educational buildings

This case study investigates the S.Ş.D. Vocational School of Higher Education Building, an educational facility located in Safranbolu, Türkiye (Fig. 1). The building was selected due to its representative characteristics of educational institutions, which possess distinct energy consumption profiles when compared to residential or commercial structures. Educational buildings typically exhibit variable occupancy patterns, elevated internal heat gains resulting from occupants and electronic equipment, and specific ventilation and lighting requirements. These attributes make such facilities particularly suitable for evaluating the effectiveness of passive design strategies aimed at enhancing energy efficiency and indoor thermal comfort.

The building under study is a multi-story educational facility with an approximate gross floor area of 4,712 m², oriented along the cardinal directions, with its principal façades facing north and south (Fig. 2). Located in Safranbolu, the building is subject to a cold climate, characterized by cold winters, necessitating the implementation of heating strategies throughout the year. Under these climatic conditions, optimizing the building's thermal envelope, glazing systems, and ventilation strategies plays a critical role in reducing overall energy consumption while enhancing indoor environmental quality.

2.1.2. Baseline energy performance assessment

Prior to the implementation of any passive design strategies, a baseline energy performance analysis was conducted using DesignBuilder, a dynamic building simulation tool that incorporates the EnergyPlus engine. The baseline model was developed to accurately reflect the building's existing operational conditions and thermal performance under current use patterns (Fig. 3).

The simulation was configured to reflect realistic operational conditions, assuming a 24-hour usage schedule to account for extended occupancy beyond standard working hours due to academic and administrative activities.

Fig. 1. Building of Safranbolu Şefik Dizdar (S.Ş.D.) Vocational School of Higher Education

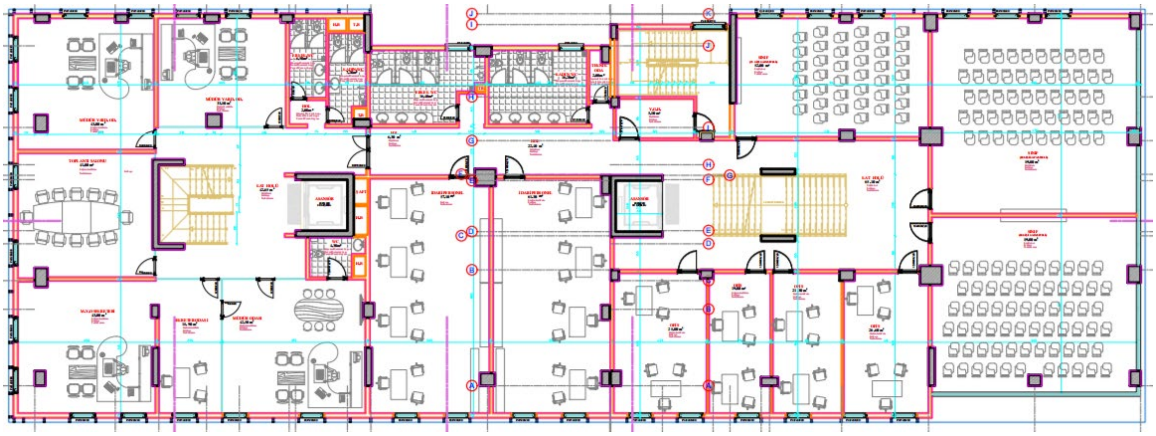

Fig. 2. The ground floor plan

Fig. 3. Building model in design builder

Indoor thermal comfort parameters were maintained in accordance with ASHRAE Standard 55, with heating and cooling setpoints set at 18°C and 24°C, respectively. The existing glazing system consisted of 6+12+6 mm reflective double glazing, offering moderate thermal insulation but limited solar control capabilities. Exterior walls included 5 cm of insulation, which falls below recommended standards for cold climate regions and contributes to elevated heating loads during winter. An air tightness value of 1 Air Change per Hour (ACH) was applied, representing a moderate level of air infiltration consistent with prevailing construction practices. The thermal properties of all building envelope components are detailed in Table 1.

The results of the baseline simulation revealed that the building experiences substantial heating loads, primarily driven by excessive heat loss during winter. The inadequate thermal performance of the building envelope, particularly the insufficient wall insulation and significant air infiltration, contributed to elevated heating demand in colder months. Furthermore, the simulation identified uneven indoor temperature distribution across different zones, highlighting the need for improved thermal comfort and energy performance. These findings confirm that targeted modifications to the building envelope, window-to-wall ratio, glazing specifications can substantially enhance thermal performance and contribute to significant reductions in overall energy consumption.

Table 1. Thermal properties of layers in existing model

	Layers	Thermal Conductivity (W/mK)	Thickness (m)
Wall	Brick cladding	0.54	0.015
	XPS thermal insulation	0.034	0.05
	Exterior plaster	0.21	0.02
	Bims+Brick	0.16	0.2
	Interior plaster	0.21	0.02
Floor	Leveling Screed	0.87	0.035
	Concrete Slab	2.5	0.15
	XPS Insulation	0.035	0.05
	Artificial Marble	1.3	0.02
	Plaster	0.21	0.02
Roof	Trapezoidal Aluminum Sheet	230	0.003
	Elastomeric Resin-Based Waterproofing	0.4	0.001
	Bituminous Sheet	0.19	0.002
	Glass Wool Insulation	0.045	0.006
	Roof Construction (Concrete)	2.5	0.15
	Plaster	0.21	0.02
Window	Aluminum Framed Reflective Glass (6+12+6 mm)	3.7	0.024
WWR	E:0.38 W:0.70 N:0.58 S:0.43		

*Source: TS 825

2.1.3. Assumptions for energy modeling

To ensure the accuracy and reliability of the energy performance simulations, several key assumptions were established concerning building operation, occupant behavior, and environmental conditions. The simulation incorporated historical climate data specific to Safranbolu, obtained from the EnergyPlus Weather Data (EPW) database, to reflect local climatic conditions with fidelity. Occupancy patterns were modeled based on actual usage profiles of various functional spaces within the building, including classrooms, laboratories, and administrative offices, each assigned distinct operational schedules to represent real-world activity levels.

The lighting and HVAC systems were assumed to operate according to scheduled demand rather than continuous operation, thereby simulating more realistic control strategies aimed at optimizing energy consumption while maintaining indoor environmental quality. An air infiltration rate of 1 Air Change per Hour (ACH) was applied to represent typical air leakage through windows, doors, and construction joints, in accordance with existing building conditions. These assumptions were critical in constructing a simulation model that closely reflects the actual energy performance of the building under current operational circumstances. It is important to acknowledge that, in line with conventional practices in building energy simulation, this study primarily concentrates on the internal performance of the building and its interaction with macroclimatic conditions derived from historical weather data. External contextual factors, such as the presence of adjacent buildings, shading effects from surrounding topography or vegetation, and localized urban heat island phenomena, were not explicitly incorporated into the simulation model. While these elements can exert a meaningful influence on actual energy performance, their detailed modeling was beyond the scope of this preliminary assessment. Future research should consider integrating these external variables to enhance the accuracy and contextual relevance of simulation outcomes.

2.2. Development of retrofit scenarios

To improve the energy efficiency of the S.Ş.D. Vocational School of Higher Education Building, a series of passive retrofit scenarios were developed, with a primary focus on modifications to the building envelope and the optimization of glazing systems. These scenarios were systematically designed to assess the impact of various passive design strategies on the building's overall energy performance. The analysis specifically examined changes in heating and daylighting demand, and thermal comfort, providing a comprehensive evaluation of the effectiveness of each intervention under the building's existing climatic and operational conditions.

2.2.1. Scenarios 1-2: Modifying the window-to-wall ratio (WWR)

The window-to-wall ratio (WWR) is a critical design parameter that significantly influences the quantity of natural daylight entering indoor spaces, thereby impacting both visual comfort and energy consumption. Higher WWR values enhance daylight penetration, potentially reducing reliance on artificial lighting; however, they can also lead to increased cooling loads due to greater solar heat gains. In contrast, lower WWR values contribute to improved thermal insulation and reduced heat loss during winter but may necessitate increased artificial lighting due to limited daylight access. Two retrofit scenarios were developed to evaluate the energy performance implications of WWR modifications:

Scenario 1: In this scenario, the Window-to-Wall Ratio (WWR) on the south-facing façades was increased by 10% to enhance daylight penetration within interior spaces (S-WWR: 0.43+0.10).

Scenario 2: The WWR was reduced by 10% on south façade to enhance thermal insulation and minimize both heating losses in winter (S-WWR:0.43-0.10).

2.2.2. Scenarios 3-5: Upgrading glazing systems

In this study, glazing systems were selected with careful consideration of Safranbolu's predominantly heating-dominated climate, where the primary objective was to minimize winter heat losses while maintaining sufficient visible light transmittance. The existing 6+12+6 mm reflective double glazing offers only moderate thermal insulation and, due to its limited solar control, contributes to high heating loads. To address this, Low-E coated glazing systems, known for reducing conductive heat loss by reflecting infrared radiation while largely preserving visible light transmission, were evaluated. These glazing types were chosen not only for their proven high performance in heating-dominated climates but also for their wide market availability, ensuring the proposed solutions are both technically effective and practically applicable. For Scenarios 3-5, the Low-E coating is applied to surface 3 (the inner surface of the outer pane) of the double-glazing units. In line with the study's aim of "reducing heat losses through passive measures," these systems were comparatively tested to identify the most efficient retrofit options. The retrofit scenarios were designed to assess improvements in insulation, solar control, and condensation resistance, as outlined below:

Scenario 3: Replacement with Low-E double-glazed windows with a U-value of 2.4 $W/m^2 \cdot K$, designed to minimize heat loss during winter through enhanced infrared reflectivity.

Scenario 4: Upgrading to Low-E triple-glazed windows (6+12+6+12+6 mm) with a U-value of 1.9 $W/m^2 \cdot K$, designed to improve thermal insulation, enhance resistance to condensation, and reduce overall U-values.

Scenario 5: Incorporating argon gas-filled Low-E triple-glazed windows (6+12+6+12+6 mm) with a U-value of 1.6 $W/m^2 \cdot K$, designed to achieve superior thermal performance by reducing convective heat transfer within the glazing layers, while maintaining visible light transmission and preventing condensation.

2.2.3. Scenario 6: Implementing a double-skin façade (dsf) system with Low-E glazing

A double-skin façade (DSF) system integrates an additional glazed layer to create an intermediate air cavity between the exterior and interior façade surfaces. This cavity serves as a thermal buffer zone, enhancing the building's overall insulation performance, reducing cooling loads, and, when properly designed, improving the effectiveness of natural ventilation. As a passive design strategy, DSFs offer considerable potential for moderating indoor thermal conditions across different seasons.

Scenario 6: This scenario involves the implementation of a non-ventilated double-skin façade system on the south-facing façade, incorporating Low-E double glazing to enhance thermal efficiency. An 80 cm-wide air cavity was introduced between the glazing layers to retain heat during the winter months and to limit solar heat gain in the summer. The cavity functions as a static insulation layer, contributing to overall energy savings and promoting seasonal thermal balance without reliance on mechanical systems.

2.2.4. Scenarios 7-9: Cavity wall and enhancing wall insulation

Minimizing heat transfer through the building envelope is essential for reducing heating demand in winter and cooling loads in summer. This study investigates the performance implications of employing a cavity wall configuration supplemented with mineral wool insulation, in combination with different triple Low-E glazing systems. Mineral wool was selected due to its proven fire resistance, acoustic performance, and stability under varying moisture conditions. On the fenestration side, triple Low-E units with either air or argon gas fill were evaluated to determine the incremental thermal performance gains achievable within the same wall construction.

Scenario 7 incorporates a cavity wall with the addition of 7.5 cm of mineral wool insulation. This arrangement enhances the thermal resistance of the wall assembly while providing improved fire safety and acoustic comfort. In this scenario, standard glazing is retained, thereby isolating the effects of wall insulation enhancement from fenestration upgrades.

Scenario 8 builds upon the configuration in Scenario 7 by replacing the existing windows with triple Low-E air-filled glazing units. This modification is expected to significantly reduce radiative heat transfer through the glazing, while the air fill introduces additional thermal resistance. The combined improvements in wall and window performance aim to achieve notable reductions in winter heating demand.

Scenario 9 maintains the same cavity wall and mineral wool insulation configuration as Scenario 8 but replaces the air fill in the glazing units with argon gas. Due to its lower thermal conductivity compared to air, argon filling further reduces the U-value of the glazing assembly. This enables a higher level of thermal performance with minimal increases in assembly thickness, thereby minimizing both heating and cooling loads relative to the other scenarios.

The comparative analysis of these three scenarios allows for a clear assessment of the contribution of cavity wall insulation alone, as well as the incremental benefits of upgrading to triple Low-E glazing with air or argon gas fill. This integrated approach provides an evidence-based framework for optimizing wall and fenestration design in passive retrofit strategies for energy-efficient buildings

2.2.5. Scenario 10: Integrating aerogel insulation with triple-pane argon-filled glazing

Scenario 10 examines an advanced, fully integrated envelope retrofit strategy that combines a cavity wall with aerogel-based insulation and high-performance triple-pane, argon-filled Low-E glazing. Aerogel was selected due to its exceptionally low thermal conductivity, among the lowest of any commercially available insulation material, enabling significant thermal resistance within minimal thickness. This characteristic makes it particularly advantageous in retrofit applications where increasing wall thickness is constrained by architectural or spatial limitations. Additionally, aerogel offers hydrophobic properties, long-term stability, and resistance to compression, ensuring consistent insulating performance over the building's service life.

In this configuration, the cavity wall serves as the base structural assembly, while the aerogel layer minimizes conductive heat transfer through the opaque portions of the envelope. The triple-pane, argon-filled Low-E glazing further reduces heat losses through fenestration by combining low-emissivity coatings, multiple insulating layers, and an inert gas fill with lower thermal conductivity than air. By addressing both opaque and transparent elements of the building envelope with state-of-the-art passive technologies, Scenario 10 aims to achieve maximum reductions in heating demand, while improving indoor thermal comfort and overall energy efficiency.

2.3. Energy performance simulation and analysis

In this study, the DesignBuilder software was used to evaluate the building's energy performance. DesignBuilder integrates the EnergyPlus simulation engine and enables dynamic, hourly-based energy modeling. Its selection was motivated by its ability to deliver high-resolution analysis of heating loads and daylighting performance under a variety of climatic and operational scenarios.

While several commercially available tools, such as Autodesk Insight, Tally, and Sefaira, are widely used for comparing passive and active design strategies, they often rely on static or semi-dynamic assumptions. These simplified methods may overlook complex thermal interactions, internal heat gains, and environmental variability. In contrast, the EnergyPlus-based approach employed in this study allows for a more precise and detailed assessment of both the individual and combined impacts of passive design strategies on energy consumption and thermal comfort.

2.3.1. Simulation setup

Each retrofit scenario was simulated under consistent boundary conditions, with variations applied exclusively to the building envelope, glazing configurations, and insulation strategies. To ensure climatic accuracy, all simulations utilized historical weather data specific to Safranbolu, obtained from the EnergyPlus Weather Data (EPW) database. This approach enhances the reliability of the results by grounding them in real-world environmental conditions. The simulation setup incorporated the following key parameters:

Building Operation: A 24-hour usage schedule was applied to reflect both academic and administrative functions, accounting for extended occupancy beyond standard working hours.

Indoor Thermal Comfort Standards: Heating and cooling setpoints were maintained between 18°C and 24°C, in accordance with ASHRAE Standard 55, to ensure occupant comfort.

Occupancy Patterns: Distinct occupancy schedules were defined for classrooms, laboratories, and administrative offices to reflect actual usage trends and space utilization.

Internal Heat Gains: Thermal contributions from lighting systems, electronic equipment, and occupant activities were incorporated to represent internal loads accurately.

Air Tightness Factor: An air infiltration rate of 1 Air Change per Hour (ACH) was assumed, reflecting the current construction quality and envelope sealing characteristics of the existing building.

2.3.2. Performance metrics for analysis

Each retrofit scenario was evaluated using a set of defined Key Performance Indicators (KPIs) to quantify the effectiveness of passive design strategies in improving building energy performance. The primary KPIs included:

Heating Loads: Seasonal variations in heating demand were analyzed to identify potential energy savings achieved through modifications to the building envelope, glazing systems, and insulation. These values provide insights into the improvements in thermal efficiency resulting from each passive intervention.

Daylighting Energy Load: The extent of natural daylight penetration was assessed to ensure that changes to the window-to-wall ratio (WWR) and glazing specifications did not compromise visual comfort or increase reliance on artificial lighting. This KPI was critical in evaluating the balance between daylight utilization and thermal performance.

A defining characteristic of Safranbolu's climate is its relatively mild summer season, during which ambient temperatures rarely necessitate substantial active cooling. Consequently, space heating represents the predominant energy demand throughout the year. Within this climatic context, the primary objective of the study, and the central focus of the detailed performance analysis, was to assess the extent to which passive design strategies could effectively reduce heating and lighting energy loads, which constitute the major components of the baseline building's overall energy consumption.

Although cooling demand was included in the comprehensive energy simulations performed using DesignBuilder and EnergyPlus, detailed analysis and scenario-specific reporting of cooling loads were excluded from the core scope of this study, as cooling was determined to be a relatively minor contributor to the building's annual energy profile in this regional context.

3. Results

This section presents the outcomes of the simulation-based energy performance analysis for the existing building and examines the effectiveness of a range of passive retrofit strategies. The findings reveal baseline inefficiencies in the current building configuration and quantify the potential energy savings achievable through targeted interventions. The analysis includes a comparative evaluation of key passive design measures, such as adjustments to the window-to-wall ratio (WWR), upgrades to glazing systems, the implementation of a double-skin façade (DSF), and the application of advanced insulation materials. Each scenario is assessed in terms of its impact on heating loads, daylighting performance, and overall thermal efficiency, providing critical insights for the development of low-energy retrofit solutions in educational buildings located in cold climate regions.

3.1. Baseline energy performance of the existing building

Prior to the implementation of any retrofit strategies, the baseline energy performance of the existing S.Ş.D. Vocational School of Higher Education building was evaluated to identify inefficiencies related to heating and cooling. Simulation results indicated an annual heating demand of 61.22 kWh/m² and an annual lighting demand of 34.36 kWh/m². The building exhibited elevated heating loads during the winter months, primarily due to significant heat loss through the building envelope and uncontrolled air infiltration.

The principal sources of energy loss were identified as follows; the existing 6+12+6 mm reflective double glazing provides moderate thermal insulation but lacks effective solar control, leading to substantial heat loss during the heating season. The wall assembly, incorporating only 5 cm of insulation, was determined to be insufficient for achieving adequate thermal resistance, resulting in excessive heat transfer. An air exchange rate of 1 Air Change per Hour (ACH) further exacerbates heating and cooling demand by increasing the load on HVAC systems to maintain indoor comfort conditions.

These findings underscore the potential for significant energy savings through passive retrofit interventions, including the installation of high-performance glazing, enhanced thermal insulation, and optimized window-to-wall ratios (WWR). Such improvements are expected to reduce both heating and cooling loads, while also contributing to improved indoor thermal comfort and overall energy efficiency.

3.2. Energy performance of the scenarios 1-2

The Window-to-Wall Ratio (WWR) is a critical design parameter that significantly influences the balance between natural daylight availability, solar heat gains, and overall energy consumption in buildings. Adjusting WWR values allows for the optimization of either daylight penetration or thermal performance, depending on the building's specific energy efficiency goals. In this study, two alternative WWR adjustment scenarios were developed and analyzed to assess their impact on lighting and heating energy demands. The comparative energy performance results of the baseline model, along with those of Scenario 1 and Scenario 2, are presented in Table 2.

In Scenario 1, the Window-to-Wall Ratio (WWR) on the south-facing façade was increased with the aim of enhancing daylight penetration into interior spaces.

Table 2. The energy performance results of the baseline model and Scenarios 1 and 2

	Annual Lighting Demand	Annual Heating Demand
Baseline	34.36 kWh/m^2	61.22 kWh/m^2
Scenario 1	34.56 kWh/m^2	62.39 kWh/m^2
Scenario 2	34.02 kWh/m^2	60.08 kWh/m^2

Consequently, the annual lighting energy demand exhibited a slight increase, rising from 34.36 kWh/m² to 34.56 kWh/m².

The annual heating demand increased from 61.22 kWh/m² to 62.39 kWh/m², primarily due to elevated thermal losses through the enlarged glazed surfaces, particularly during the winter season. While improved daylighting performance contributes positively to visual comfort and indoor environmental quality, the expanded window area introduces the potential for increased cooling loads during the summer months due to greater solar heat gains. Although cooling performance was not within the primary scope of this analysis, this emerging risk underscores the need for further investigation.

Overall, the results suggest that increasing WWR on the south façade can be advantageous in terms of daylight utilization but comes at the cost of higher heating energy consumption. Therefore, this approach may be more suitable for buildings located in milder winter climates.

It is also important to note that, although Scenario 1 aimed to improve daylight performance through a higher WWR, the design and optimization of external shading devices, such as overhangs or vertical fins, were not integrated into this phase of the analysis. As a result, the strategy’s full energy-saving potential remains underutilized. Incorporating climate-responsive external shading solutions in future design iterations could not only enhance daylighting efficiency but also play a critical role in limiting undesired solar heat gain, particularly during warmer seasons. This presents a valuable direction for future research and refinement of passive design strategies.

In Scenario 2, the Window-to-Wall Ratio (WWR) was reduced in order to decrease the total glazed surface area, thereby enhancing the building envelope’s thermal insulation and minimizing heat loss during the winter season. This intervention led to a slight reduction in lighting energy demand, from 34.36 kWh/m² to 34.02 kWh/m², as the diminished daylight penetration necessitated greater reliance on artificial lighting in certain interior spaces.

More significantly, the annual heating demand decreased from 61.22 kWh/m² to 60.08 kWh/m², reflecting improved thermal performance attributable to reduced conductive heat transfer and air infiltration through the façade. Although the reduction in WWR limited the potential for passive solar heat gain, an element typically advantageous during winter months, the overall outcome yielded a net decrease in heating load.

However, the effectiveness of this approach depends on the implementation of complementary daylighting strategies. Without optimized interior lighting design or daylight-responsive control systems, the increased reliance on artificial lighting could partially offset the energy savings achieved through improved thermal insulation.

Overall, Scenario 2 demonstrates superior performance in reducing heating energy demand and is particularly well-suited for cold climate regions where winter heat retention is critical. Nonetheless, an integrative approach, combining façade optimization with advanced lighting design, is essential to maximize energy efficiency without compromising visual comfort.

The selection of glazing systems is a critical determinant in achieving an optimal balance between thermal insulation, daylighting efficiency, and overall energy performance in buildings. Variations in glazing properties, specifically the U-value, Solar Heat Gain Coefficient (SHGC), and Visible Light Transmittance (VLT), substantially influence the building’s energy profile. These parameters govern the extent of solar heat gain, the effectiveness of thermal insulation, and the quality and quantity of daylight admitted into interior spaces. Consequently, they have a direct impact on both heating and lighting energy demands, underscoring the importance of precise glazing selection in passive design strategies.

3.3. Energy performance of the scenarios 3-5

To evaluate the impact of glazing system upgrades on building energy performance, three alternative low-emissivity (Low-E) glazing configurations were assessed in comparison to the baseline reflective double-glazing system. The primary objective was to determine the most effective glazing solution for minimizing heating energy demand while ensuring sufficient daylight availability. The corresponding lighting and heating energy demands for each scenario are summarized in Table 3.

The selection of glazing systems is a critical determinant in achieving an optimal balance between thermal insulation, daylighting efficiency, and overall energy performance in buildings. Variations in glazing properties, specifically the U-value, Solar Heat Gain Coefficient (SHGC), and Visible Light Transmittance (VLT), substantially influence the building's energy profile. These parameters govern the extent of solar heat gain, the effectiveness of thermal insulation, and the quality and quantity of daylight admitted into interior spaces. Consequently, they have a direct impact on both heating and lighting energy demands, underscoring the importance of precise glazing selection in passive design strategies.

In Scenario 3, Low-E double-glazed windows with air-filled cavities were introduced. This configuration resulted in a substantial reduction in annual lighting energy demand, decreasing from 34.36 kWh/m² to 31.62 kWh/m², indicating enhanced visible light transmittance and, consequently, reduced reliance on artificial lighting. In parallel, the annual heating demand decreased significantly, from 61.22 kWh/m² to 54.86 kWh/m², demonstrating a considerable improvement in thermal insulation compared to the baseline glazing system.

These outcomes confirm that Low-E coatings effectively mitigate conductive heat loss while allowing sufficient solar gain to support passive heating strategies. Thus, Scenario 3 presents a favorable balance between daylight utilization and thermal performance. However, it is important to note that while this glazing type performs well under moderate winter conditions, its insulation capacity may be inadequate for buildings located in severe cold climate zones, where more advanced glazing technologies, such as triple-glazing systems, may be necessary to achieve the desired energy savings.

In Scenario 4, Low-E triple-glazed windows with air-filled cavities were implemented. This configuration led to a slight increase in annual lighting energy demand, rising from 31.62 kWh/m² (Scenario 3) to 33.75 kWh/m², corresponding to a 6.73% increase. The reduction in visible light transmittance is attributed to the additional glazing layer, which diminishes daylight penetration. However, this trade-off was offset by a notable improvement in thermal insulation, as annual heating demand declined from 54.86 kWh/m² to 50.64 kWh/m², representing a 7.70% reduction relative to Scenario 3, and a 17.3% decrease when compared to the baseline condition (61.22 kWh/m²).

These findings suggest that while triple glazing with air-filled cavities enhances insulation performance in winter, it slightly compromises daylight availability.

Table 3. The energy performance results of the baseline model and Scenarios 3, 4 and 5

	Annual Lighting Demand	Annual Heating Demand
Baseline	34.36 kWh/m^2	61.22 kWh/m^2
Scenario 3	31.62 kWh/m^2	54.86 kWh/m^2
Scenario 4	33.75 kWh/m^2	50.64 kWh/m^2
Scenario 5	33.75 kWh/m^2	48.73 kWh/m^2

Therefore, the integration of daylight-responsive control systems and climate-adaptive shading strategies becomes critical to mitigate increased lighting energy consumption.

In Scenario 5, Low-E triple-glazed windows with argon gas filling were tested. Lighting demand remained constant at 33.75 kWh/m², confirming that the substitution of air with argon gas does not influence visible light transmission. However, annual heating demand was further reduced to 48.73 kWh/m², yielding a 3.77% improvement compared to Scenario 4, and a 20.38% reduction compared to the baseline model.

The enhanced performance is attributed to argon's lower thermal conductivity (~0.016 W/m·K) relative to air (~0.024 W/m·K), which significantly reduces conductive heat losses through the glazing units. Among all glazing scenarios analyzed, Scenario 5 demonstrated the greatest reduction in heating energy demand, making it the most thermally efficient solution, particularly for buildings located in heating-dominant climates.

3.4. Energy performance of the scenario 6

The double-skin façade (DSF) system constitutes an advanced passive architectural strategy designed to enhance thermal insulation, facilitate natural ventilation, and enable effective solar control. By incorporating an additional layer of glazing, the DSF forms an intermediate ventilated air cavity between the interior and exterior façades. This buffer zone plays a crucial role in reducing heat loss during winter and mitigating solar heat gains in summer, thereby contributing to seasonal thermal stability.

In Scenario 6, a Low-E double-glazed DSF system was implemented on the south-facing façade to evaluate its effectiveness in improving the building's thermal performance and overall energy efficiency. The DSF in this configuration included an 80 cm non-ventilated cavity, designed to trap air and enhance thermal resistance.

Table 4 presents a comparative analysis of lighting and heating energy demand between the baseline model and the DSF-enhanced configuration in Scenario 6. The results provide insight into the trade-offs between enhanced insulation and potential reductions in daylight penetration associated with DSF systems.

In Scenario 6, the application of a Low-E double-glazed double-skin façade (DSF) system led to a measurable shift in both lighting and heating energy performance indicators. Specifically, annual lighting energy demand increased by approximately 4.3%, rising from 34.36 kWh/m² to 35.82 kWh/m². This increase is attributed to the reduced daylight transmittance resulting from the additional glazing layer, which, while beneficial for thermal buffering, introduced shading effects that diminished natural daylight penetration and subsequently heightened reliance on artificial lighting.

In contrast, annual heating energy demand was significantly reduced by 25.9%, decreasing from 61.22 kWh/m² to 45.38 kWh/m². This substantial improvement is primarily attributed to the thermal buffer created by the 80 cm non-ventilated air cavity between the two glazing layers, which effectively mitigated conductive and convective heat losses through the façade during colder periods. Moreover, the incorporation of Low-E coatings further enhanced thermal performance by minimizing long-wave radiative heat transfer.

These results highlight the efficacy of DSF systems with Low-E glazing in heating-dominant climates, where reducing winter heat loss is a key energy performance objective.

Table 4. The energy performance results of the baseline model and Scenario 6

	Annual Lighting Demand	Annual Heating Demand
Baseline	34.36 kWh/m^2	61.22 kWh/m^2
Scenario 6	35.82 kWh/m^2	45.38 kWh/m^2

However, the increase in lighting energy consumption also emphasizes the need for integrated daylighting strategies, such as light shelves or smart shading systems, to compensate for diminished daylight availability and ensure visual comfort.

Future research is recommended to explore the comparative benefits of ventilated versus non-ventilated DSF configurations, as well as their dynamic interactions with solar orientation and seasonal variations. Such investigations will be critical in optimizing the balance between thermal insulation and daylight utilization within high-performance façade systems.

3.5. Energy performance of the scenarios 7, 8 and 9

The building envelope plays a pivotal role in regulating thermal performance, directly influencing heating energy demand and indoor environmental quality. Achieving Net-Zero Energy Building (NZEB) standards requires a highly insulated envelope capable of minimizing heat losses while ensuring occupant comfort. This section evaluates the impact of retrofitting the envelope through the use of cavity wall construction supplemented with mineral wool insulation, as well as the integration of high-performance triple Low-E glazing systems, under cold-climate conditions.

Scenario 7 involves the implementation of a cavity wall supplemented with 7.5 cm of mineral wool insulation. This intervention resulted in a modest increase in lighting energy demand to 34.67 kWh/m² (0.9% above the baseline of 34.36 kWh/m²), likely due to slight changes in interior surface reflectance affecting daylight distribution. In contrast, annual heating demand decreased by 18.7%, from 61.22 kWh/m² to 49.74 kWh/m², indicating a marked improvement in thermal resistance. The reduction in thermal conductivity of the modified wall assembly effectively limited heat transfer through the opaque façade, improving indoor comfort and lowering winter heating loads.

Scenario 8 builds upon Scenario 7 by integrating triple-pane, Low-E air-filled glazing. Lighting demand remained constant at 34.67 kWh/m², demonstrating that the glazing upgrade did not compromise daylight availability. Annual heating demand was reduced to 42.48 kWh/m², representing a 30.6% decrease relative to the baseline. This improvement can be attributed to the synergistic effect of combining cavity wall insulation with advanced glazing technology. The Low-E coatings minimized long-wave radiative heat losses while allowing high visible light transmission, thereby enhancing both energy efficiency and daylight performance.

Scenario 9 retains the same cavity wall and mineral wool insulation configuration but replaces the air-filled glazing with triple-pane, Low-E argon-filled units. Lighting demand again remained stable at 34.67 kWh/m², confirming that the type of inert gas fill has no measurable impact on daylight transmittance (Table 5). Heating demand, however, decreased further to 41.59 kWh/m², corresponding to a 32.1% reduction from the baseline. The enhanced performance of argon-filled glazing is attributed to argon's lower thermal conductivity compared to air, which further suppresses convective heat transfer through the transparent envelope components.

Among the configurations examined, Scenario 9, combining cavity wall insulation with triple-pane, Low-E argon-filled glazing, yielded the greatest reduction in annual heating demand while maintaining acceptable lighting energy levels.

Table 5. The energy performance results of the baseline model and Scenarios 7, 8 and 9

	Annual Lighting Demand	Annual Heating Demand
Baseline	34.36 kWh/m^2	61.22 kWh/m^2
Scenario 7	34.67 kWh/m^2	49.74 kWh/m^2
Scenario 8	34.67 kWh/m^2	42.48 kWh/m^2
Scenario 9	34.67 kWh/m^2	41.59 kWh/m^2

These results confirm its suitability for cold-climate retrofit applications, where heating demand dominates the overall energy profile.

In cold-climate regions, where heating demand constitutes the dominant share of building energy consumption, the integration of a cavity wall with 7.5 cm mineral wool insulation and argon-filled triple-pane Low-E glazing emerges as the most effective passive retrofit strategy for improving both energy efficiency and thermal performance. This combined configuration substantially reduces heat loss through both opaque and transparent elements of the building envelope, while preserving adequate daylight availability and avoiding increased dependence on artificial lighting. To promote large-scale adoption, future research should incorporate comprehensive cost–benefit assessments and evaluate long-term payback periods, with particular emphasis on applications in educational facilities, which often present complex operational schedules and variable thermal behavior.

3.6. Energy performance of the scenario 10

Scenario 10 investigates an advanced passive retrofit configuration in which aerogel insulation is incorporated into a cavity wall assembly and combined with triple-pane, argon-filled Low-E glazing. Aerogel was selected for its exceptionally low thermal conductivity, among the lowest of any commercially available insulation material, allowing substantial thermal resistance to be achieved within a minimal thickness. Its slim profile makes it particularly advantageous for retrofit applications where increasing wall thickness is constrained by architectural or spatial limitations. In this scenario, the integration of high-performance glazing further enhances the thermal barrier by reducing radiative and conductive heat losses through fenestration.

Table 6 presents the comparative results for annual lighting and heating energy demands between the baseline condition and Scenario 10. Lighting demand increased slightly from 34.36 kWh/m² to 34.67 kWh/m², consistent with other scenarios employing cavity wall construction. This marginal change is likely due to subtle alterations in interior surface reflectance and wall composition, which may slightly reduce daylight penetration. In contrast, annual heating demand dropped markedly from 61.22 kWh/m² to 39.84 kWh/m², corresponding to a 34.9% reduction. This significant improvement is primarily attributable to the exceptional insulating capacity of the aerogel layer, which despite a thickness of only 2 cm, substantially limited conductive heat transfer through the opaque envelope components.

The addition of triple-pane, argon-filled Low-E glazing provided a further reduction in heat losses through the transparent envelope by lowering both long-wave radiative transfer and convective heat flow within the glazing unit. This combination achieved one of the highest thermal performance levels among all retrofit configurations assessed, particularly benefiting heating-dominant climates. While the modest increase in lighting energy demand represents a minor trade-off, the overall energy savings from reduced heating requirements substantially outweigh this effect.

These findings reinforce the potential of aerogel-based insulation, when paired with high-performance glazing, as one of the most effective passive retrofit solutions for reducing heating energy demand in existing buildings. However, even such high-performing envelope strategies alone may not suffice to meet Net-Zero Energy Building (NZEB) targets.

Table 6. The energy performance results of the baseline model and Scenario 10

	Annual Lighting Demand	Annual Heating Demand
Baseline	34.36 kWh/m^2	61.22 kWh/m^2
Scenario 10	34.67 kWh/m^2	39.84 kWh/m^2

For broader implementation, future research should include comprehensive cost–benefit assessments, life cycle analyses, and evaluations of the long-term durability and economic feasibility of aerogel-based systems across diverse building typologies.

4. Discussion

Each retrofit scenario was developed to assess targeted modifications involving the window-to-wall ratio (WWR), glazing configurations, façade systems, and insulation strategies. Table 7 and Fig. 3 present the resulting annual lighting and heating energy consumption for each scenario, benchmarked against the baseline model to determine their relative effectiveness in reducing energy demand.

The simulation results for WWR adjustments reveal the expected trade-off between daylight access and thermal performance.

Table 7. The energy performance results of all scenarios

	Annual Lighting Demand	Change (%)	Annual Heating Demand	Change (%)
Baseline	34.36 kWh/m^2	0	61.22 kWh/m^2	0
Scenario 1	34.56 kWh/m^2	0.58	62.39 kWh/m^2	1.91
Scenario 2	34.02 kWh/m^2	-0.99	60.08 kWh/m^2	-1.86
Scenario 3	31.62 kWh/m^2	-7.97	54.86 kWh/m^2	-10.38
Scenario 4	33.75 kWh/m^2	-1.78	50.64 kWh/m^2	-17.28
Scenario 5	33.75 kWh/m^2	-1.78	48.73 kWh/m^2	-20.4
Scenario 6	35.82 kWh/m^2	4.25	45.38 kWh/m^2	-25.87
Scenario 7	34.67 kWh/m^2	0.9	49.74 kWh/m^2	-18.75
Scenario 8	34.67 kWh/m^2	0.9	42.48 kWh/m^2	-30.61
Scenario 9	34.67 kWh/m^2	0.9	41.59 kWh/m^2	-32.06
Scenario 10	34.67 kWh/m^2	0.9	39.84 kWh/m^2	-34.92

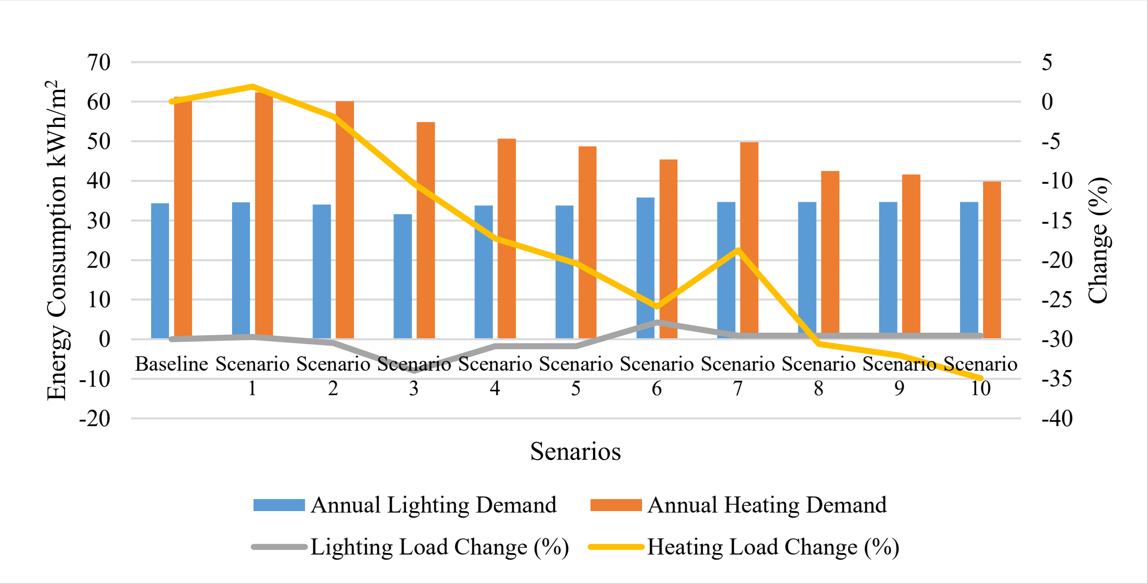

Fig. 3. Energy consumption analysis: Baseline vs. improved scenarios

Increasing the WWR on south-facing façades (Scenario 1) resulted in a 1.9% increase in annual heating demand, whereas reducing the WWR (Scenario 2) yielded a 1.9% decrease. These findings are consistent with the observations of Tzempelikos and Athienitis [39], who reported that higher WWR values in cold climates increase conductive heat losses through glazing, and with Goia [40], who demonstrated that lower WWRs improve insulation performance but may marginally increase reliance on artificial lighting. In this study, Scenario 2 exhibited only a minimal change in lighting demand, suggesting that daylight availability remained adequate even with reduced glazing area, consistent with Konis [41], who highlighted the role of daylight-responsive lighting controls in mitigating such effects.

Upgrading glazing systems produced more substantial energy savings. Transitioning from Low-E double glazing (Scenario 3) to Low-E triple glazing (Scenario 4) reduced heating demand from 61.22 kWh/m² to 50.64 kWh/m², a 17.3% improvement. The addition of argon gas in Scenario 5 further lowered heating demand to 48.73 kWh/m², corresponding to a 20.4% reduction relative to the baseline. These results align with previous research by Arasteh et al. [42] and Cuce & Riffat [43], which demonstrated that Low-E coatings reduce long-wave radiative heat transfer, and that argon-filled glazing suppresses convective heat transfer within glazing cavities. The additional 3.1% improvement from Scenario 4 to Scenario 5 supports the findings of Cuce & Riffat [43], who noted the enhanced insulating effect of inert gas fills in multi-pane systems.

Scenario 6 employed a double-skin façade (DSF) system, achieving a 25.9% reduction in heating demand. This outcome is consistent with Saelens et al. [44], who reported 20–30% energy savings with DSF systems depending on design and ventilation strategies. However, lighting demand increased to 35.82 kWh/m² (a 4.2% rise from baseline), reflecting the self-shading effect commonly observed in DSFs, as also documented by Gratia and De Herde [45]. To mitigate this, Loonen et al. [46] recommended integrating adaptive shading or dynamic glazing to balance solar gains with daylight availability.

Scenario 7 introduced a cavity wall with 7.5 cm mineral wool insulation, resulting in an 18.7% reduction in annual heating demand (from 61.22 kWh/m² to 49.74 kWh/m²). This confirms the significant role of improving wall thermal resistance in cold climates, in line with the findings of Rosas Flores [47], who reported up to 20% heating load reductions with higher R-value wall assemblies.

Scenario 8 combined the same cavity wall and mineral wool insulation with triple-pane Low-E air-filled glazing. This configuration achieved a 30.6% reduction in heating demand (to 42.48 kWh/m²), while lighting demand remained stable at 34.67 kWh/m², indicating that the glazing upgrade did not compromise daylight availability.

Scenario 9 retained the cavity wall and mineral wool insulation but incorporated triple-pane Low-E argon-filled glazing. Heating demand decreased further to 41.59 kWh/m², a 32.1% reduction compared to the baseline,while lighting demand again remained unchanged. The superior thermal performance of this configuration is attributed to argon's lower thermal conductivity compared to air, which reduces convective heat transfer within the glazing cavities.

The results for Scenarios 8 and 9 validate the synergistic benefits of integrating high-performance glazing with enhanced wall insulation, supporting the conclusion of Asdrubali et al. [48] that combined passive strategies offer superior energy savings compared to isolated measures.

Scenario 10 integrates a cavity wall with aerogel insulation and triple-pane, Low-E argon-filled glazing, achieving the greatest reduction in annual heating demand among all configurations, a 34.9% decrease relative to the baseline. This result confirms the exceptional thermal performance of aerogel, consistent with the findings of Baetens et al. [49] and Jelle [50], who reported thermal conductivities as low as 0.013 W/m·K, placing aerogel among the most efficient insulation materials commercially available [33, 34]. While this configuration resulted in a slight increase in lighting energy demand due to marginal reductions in daylight transmittance, the overall net energy savings highlight its effectiveness as a high-performance passive retrofit strategy.

In cold-climate regions, where space heating accounts for the majority of annual building energy consumption, Scenario 10 offers one of the most balanced solutions in terms of thermal resistance, energy efficiency, and occupant comfort. However, despite the significant reductions in heating loads, the residual energy demand still exceeds Net-Zero Energy Building (NZEB) thresholds. This finding underscores that passive measures alone are insufficient to achieve full NZEB compliance and should be complemented with renewable energy systems or hybrid passive–active solutions.

Despite these significant improvements, the results reveal a critical limitation: passive design strategies alone are insufficient to achieve Net-Zero Energy Building (NZEB) performance. While they substantially improve thermal resistance and reduce energy losses, passive measures cannot fully eliminate dependence on external energy sources. Bridging this gap requires integrating active renewable energy systems, such as photovoltaic (PV) panels, solar thermal collectors, and hybrid renewable solutions. Deng et al. (2014) emphasize that a hybrid approach,combining passive and active measures,is essential to meeting NZEB targets [51].

The incorporation of solar PV systems offers a practical means of enhancing energy self-sufficiency. Whether installed as rooftop arrays, façade-mounted systems, or integrated into the building envelope as building-integrated photovoltaics (BIPV), PV technology can meet 60–100% of a building's total electricity demand, depending on system capacity, efficiency, and climatic conditions. Similarly, solar thermal systems for domestic hot water production and HVAC support can further reduce heating loads; Hernández and Kenny [52] report that when coupled with passive envelope improvements, solar thermal collectors can deliver up to an additional 30% energy savings.

Although the present study primarily addresses operational energy savings, it is important to account for the embodied energy and carbon emissions associated with material production, transportation, and installation. High-performance materials such as aerogel, despite their superior insulating properties, may have a higher embodied environmental cost than conventional insulation alternatives. To ensure that retrofit strategies are both energy-efficient and environmentally responsible, future research should incorporate a comprehensive Life Cycle Assessment (LCA) that evaluates operational and embodied energy, as well as the carbon footprint of each scenario. Such an integrative approach is essential for informing sustainable retrofit design and policymaking.

5. Conclusion

This study has demonstrated the effectiveness of a range of passive design strategies, including optimized window-to-wall ratios (WWR), advanced glazing systems, double-skin façades (DSFs), and high-performance insulation materials, in reducing heating and lighting energy demands in existing educational buildings. The results highlight that improvements to envelope insulation and glazing performance can yield substantial reductions in heating loads, with Scenario 10 (cavity wall + aerogel insulation + triple-pane Low-E argon-filled glazing) achieving the greatest decrease in annual heating demand (34.9%). These findings are consistent with previous research that underscores the exceptional thermal properties of aerogel insulation and the energy-saving potential of triple-glazed, inert gas-filled windows.

Energy storage systems and smart energy management technologies are critical enablers of NZEB performance. Battery storage allows surplus PV-generated electricity to be used during periods of low generation or peak demand, improving energy reliability. Intelligent monitoring and control systems can further optimize building operations by adjusting lighting, heating, and cooling in real time based on occupancy patterns and environmental conditions.

A hybrid strategy that integrates both passive and active measures provides a robust and scalable pathway toward NZEB achievement. Emerging technologies such as adaptive façades, combining PV panels, phase change materials (PCMs), and daylight-responsive shading, offer dynamic energy optimization beyond the capabilities of conventional static systems. To fully exploit the potential of such integrated solutions, holistic energy modeling and scenario-based optimization are essential to determine the most cost-effective retrofit strategies for various building typologies and climatic contexts.

A limitation of the present study is its focus on heating and lighting energy demand, which reflects the heating-dominant climate profile of Safranbolu. In warmer regions or during summer periods, passive measures that enhance solar gain or reduce heat loss may inadvertently increase cooling loads. Therefore, future research should evaluate these retrofit strategies in hot and mixed-humid climates to provide a balanced assessment of both heating and cooling performance.

In conclusion, while passive design principles form the foundation for improving building energy efficiency, achieving NZEB performance requires a comprehensive approach that incorporates renewable energy generation, energy storage, and intelligent control systems. Future work should investigate the economic feasibility of such hybrid retrofits through detailed cost–benefit analyses, accounting for capital investment, operational savings, payback periods, and long-term environmental impacts. Such insights are critical for policymakers, designers, and facility managers aiming to transform existing building stock into high-performance, net-zero energy assets.

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Author Contributions

M. Tuna Kayılı: Conceptualization, Methodology, Writing, Review & Editing. B. Sultan Qurraie: Simulation.

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No new data were created or analyzed in this study.

Ethics Committee Permission

Not applicable.

Conflict of Interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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