

## Article

# Exploring the Influence of Shared Socioeconomic Pathway Scenarios on School Energy Retrofits: An Emphasis on the Building Envelope

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**Abstract:** The optimization of energy consumption in response to global warming scenarios presents fundamental challenges in the built environment, particularly in Mediterranean climates, where comfort and energy efficiency require priority-based adaptation. This study examines the effectiveness of passive energy retrofit strategies applied to an educational building in Granada, Spain, accommodating both teaching and residential uses. The research uses advanced climatic data based on Shared Socioeconomic Pathways (SSPs), incorporating precise projections of climate evolution. Using simulations conducted in DesignBuilder, it evaluates three intervention packages for the building envelope—window replacement, facade insulation, and roof insulation—across three temporal scenarios: 2024, 2050, and 2080. The results indicate that passive measures could reduce heating demand by up to 90% in future scenarios, while cooling demand is projected to increase by more than 80% by the end of the century. Additionally, climate projections under the SSP scenarios show up to an 83% increase in energy demand, emphasizing the need for integrated passive and active strategies. The research includes a sensitivity analysis of the interaction between passive strategies and advanced climate scenarios. It offers decision-making models for energy retrofitting and provides replicable key insights to support energy retrofitting policies and climate resilience in the Mediterranean region.



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## 1. Introduction

The impact of energy consumption on the built environment is a growing concern in sustainability, posing challenges at the intersection of environmental, urban planning, and social issues [1,2]. Buildings are significant contributors to greenhouse gas emissions and energy consumption, directly influencing climate change and energy poverty [3]. Reducing energy consumption and adapting buildings to future climatic conditions has become a global priority for architects and engineers, who aim to balance energy efficiency with occupant comfort [4,5]. Public buildings, particularly schools, play a crucial role due to their educational and social functions and their potential to generate long-term economic and environmental benefits [6,7].

In Europe, educational buildings represent approximately 18% of non-residential structures, with the majority built before 1990, an era when climate and energy efficiency

were not prioritized [8,9]. Aging infrastructure in combination with rising temperatures, especially in southern Europe, have resulted in inadequate indoor conditions during extreme heat events [10,11]. This makes it essential to retrofit schools to address current and future climate challenges, as Mediterranean regions face increasing thermal extremes that could endanger occupant health and well-being without appropriate adaptations [12,13].

Retrofitting educational buildings presents an opportunity to improve efficiency and comfort through passive design strategies that utilize local climatic resources. Passive measures—such as solar orientation [14], natural ventilation [15], and thermal insulation [16]—are particularly effective in Mediterranean climates, where seasonal variations require tailored solutions [17,18]. These strategies offer sustainable low-cost alternatives to mechanical systems, reducing the reliance on energy-intensive methods while improving indoor comfort [19,20]. Incorporating passive measures into retrofitting ensures long-term value by lowering emissions and strengthening the climate resilience of educational facilities.

In this context, the European Union has established legislative frameworks and targets to reduce energy consumption in public buildings. Strategies such as the European Green Deal and Directive (EU) 2018/844 aim to transform buildings into nearly-zero-energy buildings (nZEB) by 2050 [21], promoting architectural interventions that incorporate both active and passive improvements into building systems. However, most initiatives to date have prioritized upgrading thermal systems, often overlooking the potential of passive strategies for optimizing comfort and energy efficiency [22,23]. Since passive design is a fundamental tool for achieving sustainable retrofitting, it is critical to integrate passive strategies that are customized to specific climatic and regional conditions.

The main aim is to assess the effectiveness of passive retrofitting strategies in improving energy efficiency and thermal comfort in educational buildings under climate change scenarios. To achieve this, the study focuses on a representative pilot case: the Santa Rosalía Preschool Center in Granada, which serves both educational and residential purposes for on-site maintenance staff. The research evaluates the energy performance of different retrofit measures applied to this building across three time periods (2024, 2050, and 2080) under the Shared Socioeconomic Pathway (SSP) climate scenarios. These scenarios represent the most recent framework of climate scenarios, although their implications for building energy performance have remained unexplored. In this regard, most scientific literature has traditionally relied on the Special Report on Emissions Scenarios (SRES) [24] and Representative Concentration Pathways (RCPs).

This approach thoroughly evaluates the current effectiveness of the proposed solutions and projects their long-term benefits and limitations in response to expected climatic variations throughout the 21st century. The study's main contribution is the development of an analytical framework to assess and plan passive energy retrofitting strategies for educational buildings in Mediterranean climatic contexts, using the Shared Socioeconomic Pathway (SSP) framework. Unlike traditional studies that rely on older frameworks such as the SRES or RCPs, this research integrates advanced SSP climate projections with passive design strategies, offering actionable insights for retrofit decision-making. By highlighting the replicability of these interventions in regions with similar conditions, it provides a roadmap for addressing similar challenges. Furthermore, the study emphasizes the critical role of passive strategies in achieving sustainable energy efficiency and climate resilience in educational buildings. As a reference for future research, this work supports the development of policies addressing both current and future climate challenges, contributing to sustainability and energy efficiency in education.

## 2. Literature Review

Energy retrofits in existing buildings hold significant potential for emission reductions. Studies from the Passivhaus Institut [25] indicate that appropriate interventions can enhance building efficiency by up to 90%, substantially decreasing energy demand and contributing to greenhouse gas (GHG) emission reductions [26,27].

The European Union has set ambitious targets to transform the building sector toward sustainability, aiming for climate neutrality by 2050, which involves achieving net-zero greenhouse gas emissions. Intermediate targets include a reduction in emissions of 55% by 2030 relative to 1990 levels [28]. These objectives encompass expanding renewable energy use, enhancing energy efficiency, and providing financial support for energy retrofit projects to reduce the environmental footprint of buildings and to improve thermal comfort for occupants [29].

Spain has implemented policies aligned with these EU objectives through the Plan Nacional Integrado de Energía y Clima (National Integrated Energy and Climate Plan; PNIEC) and the Ley de Cambio Climático y Transición Energética (Climate Change and Energy Transition Law), which emphasize the importance of optimizing energy performance and mitigating climate change effects [30]. Despite these regulatory efforts, public engagement with energy retrofitting remains limited, and there are no extensive renovations plans in the short term. This issue is particularly pronounced in educational buildings, which have unique energy characteristics and requirements, such as occupancy patterns and indoor comfort conditions that can impact the well-being and performance of students and teachers, as noted by Akkose et al. [31] y Belpoliti et al. [32].

The relationship between climate change and buildings is an area of ongoing development in the literature. Global warming and the urban heat-island effect have increased the pressure on buildings to maintain thermal comfort without resorting to excessive energy consumption. Heracleous et al. [33] highlighted that rising energy demand is driven by the widespread use of technology in classrooms, extended occupancy patterns, and a growing reliance on lighting and climate control systems. Research on specific adaptation strategies for these buildings, however, remains scarce, with few exceptions, such as recent studies conducted by Jaouaf et al. [34] and de Azevedo Correia et al. [35]. This gap exists despite the urgent need to develop viable and efficient energy retrofit evaluation models that align with energy efficiency targets.

Energy retrofitting of educational buildings in warm climates represents a critical opportunity to address both environmental sustainability and the comfort and health of occupants, as demonstrated by Gil-Baez et al. [18]. In this context, a high-quality indoor environment is essential not only for physical well-being but also for cognitive development and performance. Özbey and Turhan [36] confirmed that students' academic performance is directly influenced by their thermal comfort conditions. Consequently, energy retrofitting of these facilities not only improves energy efficiency but also fosters healthier and more productive environments, delivering additional benefits in terms of students' emotional development and academic performance [37].

Retrofitting strategies are typically divided into active measures, such as the implementation of efficient ventilation and climate control systems, and passive measures, which are tailored to evolving climates like the Mediterranean. Talaei and Sangin [29] highlighted that passive strategies include design techniques such as thermal insulation, solar shading, and the optimization of building orientation and materials. The literature review has shown that passive strategies are particularly valuable in Mediterranean climates, where improving the building's thermal envelope and incorporating shading techniques can reduce the reliance on active systems. This, in turn, decreases energy consumption and emissions, as demonstrated in studies by Heracleous et al. [33] and Serrano-Jimenez et al. [38]. Despite

the potential of retrofitting for improving energy performance and comfort in educational buildings, research on passive interventions in Mediterranean climates and their adaptation to future climate challenges remains limited. This study aims to address this gap by analyzing the long-term technical, economic, and social impacts of passive retrofitting strategies under projected climatic scenarios.

### 3. Materials and Methods

#### 3.1. Case Study

The selected case study, the Santa Rosalía Preschool Center, is a preschool building located in Granada (Figure 1). The building was constructed in 1975, before Spain's first energy efficiency regulations [39], and lacks thermal insulation in its envelope. The building consists of three floors, serving both educational and residential purposes, with an apartment for school staff living on-site (Figure 2). This tradition, rooted in schools from the second half of the 20th century in Spain, continues in some cases today, where a family manages the opening, closing, and maintenance tasks. While its primary function is educational, 72 m<sup>2</sup> of the space is designated for residential use. Table 1 provides a detailed breakdown of the envelope's construction elements, including its layers and thermal properties. Additionally, the building does not have a cooling system for the hot summer months.

**Table 1.** Thermal characterization of the building envelope.

| Element                 | Layer                  | s<br>[m] | $\lambda$<br>[W/mK] | R<br>[(m <sup>2</sup> K)/W] | U<br>[W/(m <sup>2</sup> K)] |
|-------------------------|------------------------|----------|---------------------|-----------------------------|-----------------------------|
| Wall                    | Cement mortar          | 0.010    | 0.57                | 0.24                        | 1.27                        |
|                         | Perforated brick       | 0.120    | 0.70                |                             |                             |
|                         | Air layer              | 0.050    |                     |                             |                             |
|                         | Hollow brick           | 0.120    | 0.70                |                             |                             |
|                         | Gypsum plaster         | 0.010    | 0.57                |                             |                             |
| Flat roof               | Catalan tile           | 0.015    | 1.00                | 0.16                        | 1.93                        |
|                         | Compression mortar     | 0.030    | 1.00                |                             |                             |
|                         | Air layer              | 0.150    |                     |                             |                             |
|                         | Reinforced concrete    | 0.200    | 2.5                 |                             |                             |
|                         | Gypsum plaster         | 0.020    | 0.57                |                             |                             |
| Unoccupied sloping roof | Clay tile              | 0.080    | 1.00                |                             | 3.31                        |
|                         | Compression mortar     | 0.050    | 1.00                |                             |                             |
|                         | Hollow brick           | 0.020    | 0.80                |                             |                             |
| Floor                   | Urea formaldehyde foam | 0.132    | 0.04                |                             | 1.00                        |
|                         | Cast concrete          | 0.100    | 1.13                |                             |                             |
|                         | Roof screed            | 0.070    | 0.41                |                             |                             |

#### 3.2. Proposed Energy Improvement

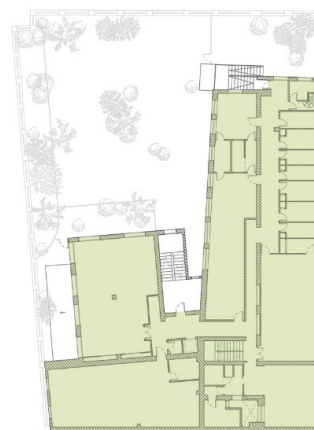
All improvements have been designed in accordance with the limit values established in the Código Técnico de la Edificación (CTE; Spanish Building Technical Code) [40]. These limit values are listed in Table 2 and correspond to climate zone C, which applies to Granada.



**Figure 1.** Selected pilot case study.



Ground floor



First floor



Second floor



Rooftop

■ School use  
■ Residential use

**Figure 2.** Floor plans of the case study.

**Table 2.** Maximum thermal transmittance values or maximum U-value established in the CTE for building envelope elements.

| Element                             | Maximum U-Value [W/(m <sup>2</sup> K)] |      |      |      |      |      |
|-------------------------------------|----------------------------------------|------|------|------|------|------|
|                                     | Winter Climate Zone                    |      |      |      |      |      |
|                                     | $\alpha$                               | A    | B    | C    | D    | E    |
| Wall                                | 0.80                                   | 0.70 | 0.56 | 0.49 | 0.41 | 0.37 |
| Elements in contact with the ground | 0.90                                   | 0.80 | 0.75 | 0.70 | 0.65 | 0.59 |
| Roof                                | 0.55                                   | 0.50 | 0.44 | 0.40 | 0.35 | 0.33 |
| Floor in contact with the air       | 0.80                                   | 0.70 | 0.56 | 0.49 | 0.41 | 0.37 |
| Window                              | 3.2                                    | 2.7  | 2.3  | 2.1  | 1.8  | 1.8  |

To retrofit the building, three solutions have been proposed: (i) window replacements; (ii) adding insulation to the facade; and (iii) adding insulation to the roof. The selection of these measures is based on common practices in the energy retrofitting of buildings in Spain [41]. A brief description of the measures considered, along with their thermal properties, is provided below:

### 3.2.1. Windows

For the glazing, a double-glazed solution was selected, consisting of 4 mm low-emissivity exterior glass, a 10 mm dehydrated gas chamber filled with argon, and 6 mm tempered, blue-tinted interior glass, with the aim of increasing the absorption of solar rays. This configuration achieves a U-value of 1.4 W/m<sup>2</sup>K and a solar factor of 39%. For the window frames, a PVC solution was chosen, offering a U-value of 1.3 W/m<sup>2</sup>K, and the air permeability was rated as class 4.

### 3.2.2. Facade Insulation

Interior insulation was chosen due to the narrow street providing access to the building, which made the installation of external insulation unfeasible. An insulated cladding system with mineral wool was therefore selected. The insulation had a thickness of 5 cm and a thermal conductivity of 0.034 W/mK. Incorporating this solution into the original facade resulted in a U-value of 0.437 W/m<sup>2</sup>K.

### 3.2.3. Flat Roof Insulation

Since the case study features two types of roofs, two distinct solutions were proposed. For the flat roof, interior insulation with mineral wool was applied, with an insulation thickness of 8 cm and a thermal conductivity of 0.039 W/mK. This solution resulted in a U-value of 0.387 W/m<sup>2</sup>K for the flat roof. For the pitched roof, insulation was installed within the air cavity, with an insulation thickness of 8 cm and a thermal conductivity of 0.04 W/mK. The resulting U-value for the pitched roof was 0.437 W/m<sup>2</sup>K.

These measures were analyzed in different packages, combining some of them to account for potential economic constraints that educational building managers may face during energy retrofitting. The following combinations were evaluated:

- Case 1: Window replacement.
- Case 2: Window replacement and facade insulation.
- Case 3: Window replacement and facade and roof insulation.

## 3.3. Selected Climate Scenarios

To conduct the future-oriented study, various climate scenarios were considered. The Intergovernmental Panel on Climate Change (IPCC) developed Shared Socioeconomic Pathways (SSPs) to analyze the effects of climate changes as well as adaptation and mitiga-

tion strategies [42,43]. These pathways, which are central to the IPCC's climate response assessments, have replaced the Representative Concentration Pathways (RCPs). Two SSP scenarios were selected for this study for the years 2050 and 2080: an unfavourable scenario (SSP5–8.5) and a favorable scenario (SSP2–4.5), as summarized in Table 3. These scenarios allow for the analysis of the projected effectiveness of energy retrofit measures applied to this building type. Current climate data were obtained using the MeteorNorm tool, while future climate scenarios were generated through the morphing method with two tools: Future Weather Generator [44] and Epwshiftr [45].

**Table 3.** A brief summary outline of selected SSP scenarios and their implications.

| Factor/Field        | 2050—SSP5–8.5                                   | 2050—SSP2–4.5                                | 2080—SSP5–8.5                                  | 2080—SSP2–4.5                                    |
|---------------------|-------------------------------------------------|----------------------------------------------|------------------------------------------------|--------------------------------------------------|
| Average Temperature | Significant increase (>3 °C above 2000 levels). | Moderate increase (~2 °C above 2000 levels). | Critical rise (>4 °C above 2000 levels).       | Controlled increase (~2.5 °C above 2000 levels). |
| Energy Use          | Dominance of fossil fuels.                      | Growing use of renewables.                   | Maximum reliance on fossil fuels.              | Predominance of sustainable energy.              |
| Biodiversity        | Severe global losses.                           | Reduction mitigated by conservation.         | Mass extinction of species.                    | Partially preserved biodiversity.                |
| Human Society       | Exacerbated inequality; high vulnerability.     | Gradual improvement in global equity.        | Severe climate migration; heightened tensions. | Moderate resilience; limited migration.          |

### 3.4. Simulation Setup and Data Analysis

The simulation setup for the case study (before and after the retrofit) was conducted using DesignBuilder version 7.3. This software integrated data on the building envelope and climatic conditions, as described earlier. Regarding activity, since the building serves dual purposes—educational and residential—rooms were differentiated based on distinct occupancy schedules. The educational schedule was set from 7:30 to 17:00, Monday to Friday, and from 11:00 to 12:00 on Saturdays and Sundays. Residential use was limited to the periods outside of school hours. Data on internal loads, including occupancy and lighting, were obtained from procedures established in the CTE. The HVAC system in the case study includes only a diesel boiler for heating and domestic hot water (DHW), with an efficiency of 0.85. The heating setpoint temperature was set at 20 °C throughout the building.

Using these inputs, simulations of the building design were performed for each climate scenario and each proposed case, resulting in a total of 25 simulations. Each simulation provided data on comfort and system loads, which were analyzed based on two key aspects: energy demand and thermal comfort (both daytime and nighttime). While energy demand data were analyzed directly from the simulation results, thermal comfort was evaluated using specific assessment methodologies. A description of these methodologies is provided below.

The Fanger method was used for nighttime comfort analysis. This method is based on the Predicted Mean Vote (PMV), which correlates human thermal sensation with environmental conditions and is derived from research conducted in controlled climates [46]. However, this method has limitations, as it was designed for activities involving some physical exertion, making it less ideal for sleeping individuals, whose metabolic rate is significantly lower (approximately 0.7 met), according to Shapiro [47]. To address this limitation, researchers such as Lan et al. [48] developed an adaptation of Fanger's model to assess nighttime thermal comfort, incorporating factors like skin temperature and respiration. The thermal load is calculated as

$$L = M - Q_{res} - Q_{skin} \quad \left[ \text{W/m}^2 \right] \quad (1)$$

where  $M$  represents the heat generated by the user;  $Q_{res}$  denotes the heat loss through respiration; and  $Q_{skin}$  refers to the heat loss through the skin.

Heat loss through respiration ( $Q_{res}$ ) is calculated using

$$Q_{res} = \frac{13.41 - 1.519 \cdot 10^{-3} p_a - 0.13 t_a}{A_D} \quad [\text{m}^2] \quad (2)$$

where  $p_a$  is the partial pressure of water vapor;  $t_a$  is the air temperature; and  $A_D$  represents the uncovered body surface area, calculated using Equation (3).

$$\begin{aligned} \text{Men} &\rightarrow A_D = 0.607l + 0.0127m - 0.0698 \quad [\text{m}^2] \\ \text{Women} &\rightarrow A_D = 0.589l + 0.0126m - 0.0461 \quad [\text{m}^2] \end{aligned} \quad (3)$$

Heat loss through the skin is divided into the loss to the environment and the loss to the mattress, calculated through simple conduction, considering the thermal conductivity ( $k$ ) and thickness ( $d$ ) of the mattress (Equation (4)). Heat loss through skin diffusion ( $E_d$ ) is characterized by Equation (5).

$$E_{cond} = \alpha k \frac{t_{sk2} - t_b}{d} \quad [\text{W/m}^2] \quad (4)$$

$$E_d = 3.074 \cdot 10^{-3} (1 - 0.8\alpha)(p_{skin1} - p_a) \quad [\text{W/m}^2] \quad (5)$$

where  $p_{skin1}$  is the saturated vapor pressure at the average skin temperature of body parts not in contact with the bed.

Additionally, heat loss through convection and radiation is calculated using Equation (6).

$$E_{C+R} = (1 - \alpha) \frac{t_{skin1} - t_o}{R_{cl} + \frac{1}{f_{cl}(h_r + h_c)}} \quad (6)$$

where  $t_{skin1}$  is the average skin temperature;  $t_o$  is the operative temperature;  $h_c$  is the convection heat transfer coefficient;  $h_r$  is the radiation heat transfer coefficient;  $f_{cl}$  is the clothing coverage factor; and  $R_{cl}$  is the thermal resistance of the bedding.

For a person laying down,  $h_r$  is approximately  $3.235 \text{ W/m}^2\text{K}$ , and  $h_c$  is calculated as

$$h_c = 0.881 |t_{skin1} - t_a|^{0.368} \quad [\text{W/m}^2\text{K}] \quad (7)$$

Therefore, using all the aforementioned equations, the equation for  $L$  can be determined as

$$L = 40 - \frac{13.41 - 1.519 \cdot 10^{-3} p_a - 0.13 t_a}{A_D} - \left( 3.074 \cdot 10^{-3} (1 - \alpha)(p_{skin1} - p_a) + (1 - \alpha) \frac{t_{skin1} - t_o}{R_{cl} + \frac{1}{f_{cl}(h_r + h_c)}} + \alpha k \frac{t_{skin2} - t_a}{d} \right) \quad (8)$$

For this study, the following specific conditions were established:

- All women were assumed to have a height of 1.6 m and a weight of 60 kg.
- The latex mattress had a thermal conductivity of  $0.048 \text{ W/mK}$  and a thickness of  $0.20 \text{ m}$ .
- The heat generated by the users ( $M$ ) was estimated at  $0.7 \text{ met}$ , which is characteristic of sleeping individuals [49].
- Following the application by Lan et al. [48],  $p_{skin1}$  was set to  $5520 \text{ Pa}$ ,  $t_{skin1}$  to  $34.6 \text{ }^\circ\text{C}$  and  $t_{skin2}$  to  $35.4 \text{ }^\circ\text{C}$ .

Once  $L$  was characterized, the PMV was obtained (Equation (9)). According to EN 16798-1 [50], thermal comfort ranges between  $-0.7$  and  $0.7$  PMV were considered, with each nighttime hour in July and August (23:00 to 8:59) analyzed. Relevant studies from the

largest global thermal comfort database suggest that there is no significant difference when the PMV falls between  $-1.0$  to  $1.0$  [51]. Thus, an alternative scenario for replicability in other schools could involve adopting or assuming the range from  $-1.0$  to  $1.0$  as being comfortable and calculating another proposal for comfort hours, as demonstrated by Li et al. [52] using their assessment index.

$$PMV = (0.303 e^{-0.036M} + 0.028) L \quad (9)$$

#### Daytime Thermal Comfort

Daytime thermal comfort was also evaluated. It was assessed using the European thermal comfort standard. Both ASHRAE 55–2017 and EN 16798–1:2019 serve as international standards for adaptive thermal comfort through natural ventilation. These standards rely on variations in the outdoor air temperature ( $t_{pma(out)}$ ), which is a weighted average of daily outdoor temperatures ( $T_{out,d}$ ), with a coefficient of 0.6 for mid-latitude climates. When  $t_{pma(out)}$  falls within a specific range, the indoor temperature adjusts naturally; otherwise, heating or cooling systems are required. The EN 16798-1:2019, widely used in Europe, classifies buildings into three categories: (i) category I (special buildings such as hospitals); (ii) category II (new buildings); and (iii) category III (existing buildings). The analysis procedure for this standard is outlined in Equations (10)–(16):

$$\underline{t_{pma(out)}} = (1 - \alpha) \times \sum_{d=1}^n (\alpha^{(i-1)} \times T_{out,d}) \text{ [}^\circ\text{C]} \quad (10)$$

$$\text{Upper limit (category I)} = 0.33 \times \underline{t_{pma(out)}} + 20.8[^\circ\text{C}] \quad (10 \leq \underline{t_{pma(out)}} \leq 30) \quad (11)$$

$$\text{Lower limit (category I)} = 0.33 \times \underline{t_{pma(out)}} + 15.8[^\circ\text{C}] \quad (10 \leq \underline{t_{pma(out)}} \leq 30) \quad (12)$$

$$\text{Upper limit (category II)} = 0.33 \times \underline{t_{pma(out)}} + 21.8[^\circ\text{C}] \quad (10 \leq \underline{t_{pma(out)}} \leq 30) \quad (13)$$

$$\text{Lower limit (category II)} = 0.33 \times \underline{t_{pma(out)}} + 14.8[^\circ\text{C}] \quad (10 \leq \underline{t_{pma(out)}} \leq 30) \quad (14)$$

$$\text{Upper limit (category III)} = 0.33 \times \underline{t_{pma(out)}} + 22.8[^\circ\text{C}] \quad (10 \leq \underline{t_{pma(out)}} \leq 30) \quad (15)$$

$$\text{Lower limit (category III)} = 0.33 \times \underline{t_{pma(out)}} + 13.8[^\circ\text{C}] \quad (10 \leq \underline{t_{pma(out)}} \leq 30) \quad (16)$$

For the purposes of this study, category I was used to evaluate daytime comfort. This category is intended for more vulnerable users or special buildings. As the case is an early childhood center, this category was deemed appropriate for assessing daytime conditions.

## 4. Results and Discussion

This section addresses the following key aspects for each energy retrofit scenario and their respective time horizons (2050 and 2080) under the SSP2–4.5 and SSP5–8.5 socioeconomic scenarios:

1. Energy demand. The reduction or increase in the building's energy demand for each intervention is analyzed to evaluate the potential effectiveness of the implemented improvements in terms of energy savings. This analysis helps identify the most efficient interventions and their long-term impact.
2. Thermal comfort hours. The impact of the interventions on nighttime and daytime summer thermal comfort for the building's occupants is assessed.

Firstly, the expected variation in the energy demand of the case study was analyzed considering the impact of the selected SSP scenarios. Case 1 examines the effect of window

replacement alone on the building's total cooling energy demand. This analysis compares the projected evolution of the case study without improvements (baseline case) to the modifications introduced in Case 1 (window replacement alone). Figure 3 shows the hourly distributions of energy demand, while Figure 4 presents the total results. The expected evolution of the case study without improvements shows that climate evolution will change the energy demand. These changes align with the trends reported in previous studies on the topic [24,53].

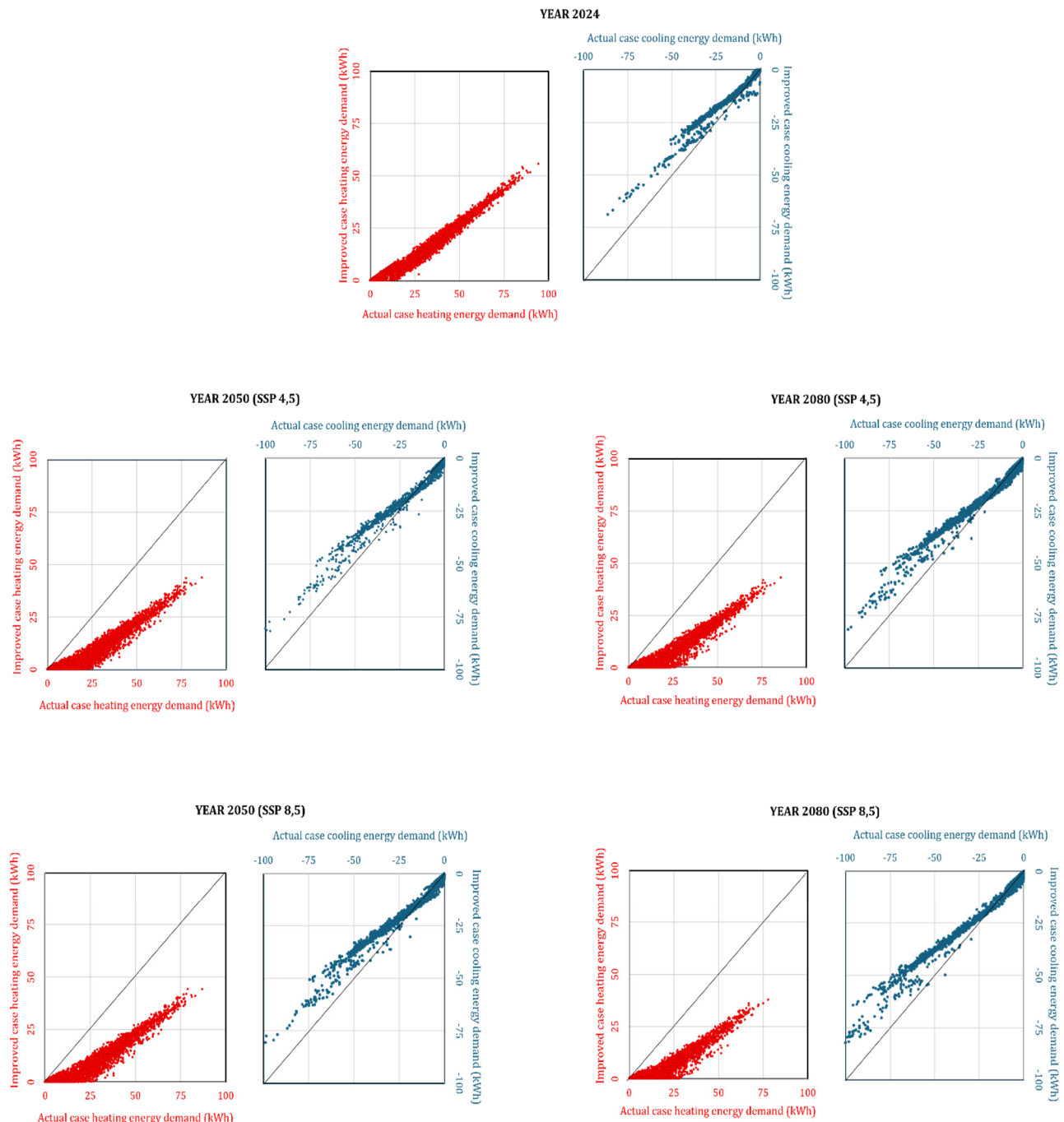


**Figure 3.** Scatter plot of the hourly heating and cooling energy demand achieved in Case 1 (window replacement).

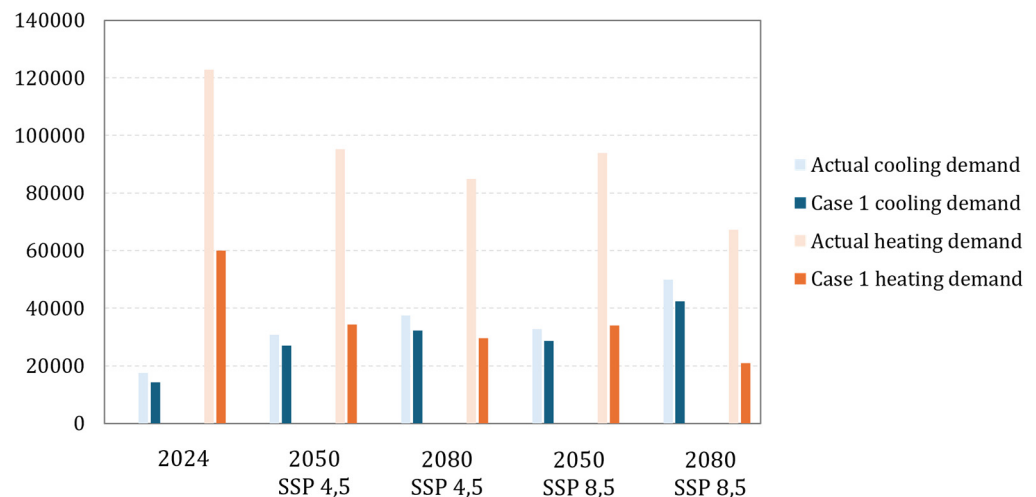


**Figure 4.** Total energy demand achieved in Case 1 (window replacement).

Cooling demand is expected to increase, while heating demand should decrease. These trends are more pronounced under the SSP scenarios. For the year 2050, an average increase in cooling demand of 4.53 kWh is projected under SSP2–4.5 and of 6.76 kWh under SSP5–8.5. This results in a differential in the average hourly values of 2.23 kWh. Such a difference was not detected under the SRES or RCP scenarios. This difference may reflect updated trends in radiative forcing under future climate conditions. Similar trends are observed in other cases. Average heating demand reductions range from 4.53 kWh to 10.97 kWh, depending on the year and scenario. These result in the annual heating energy demand potentially decreasing by up to 55,580.64 kWh by the end of the century under the evolving climate. On the other hand, cooling demand could increase by as much as 32,391.85 kWh. The projected variation in energy demand emphasizes the necessity of implementing energy improvement strategies.

As previously mentioned, this work focuses on analyzing envelope improvements, as they represent one of the most common approaches. The first case examines the use of window replacements. As observed, window replacement results in a reduction in energy demand, although the impact is not particularly significant. In the current scenario, window replacement has a more substantial effect on heating demand, as shown in the hourly energy demand values. Average hourly heating demand savings amounted to 10.76 kWh, significantly surpassing the 1.1 kWh savings achieved for cooling. This trend is also reflected in the distribution values, with an interquartile range of 18.71 kWh for heating and 0.20 kWh for cooling. As a result, annual savings were 19% for cooling and 51% for heating. Thus, this improvement led to a clear reduction in heating demand in the current scenario. Regarding future evolution under the SSP scenarios, this trend persists due to the diminishing effectiveness of window improvements. Cooling demand increases while heating demand decreases, leading to annual energy savings of 12% to 15% for cooling and 64% to 69% for heating. Although this strategy has limited applications, it may offer an economic advantage compared with other measures due to its cost-effectiveness.

Regarding Case 2 (window replacement and facade insulation), an improvement in the energy performance compared with Case 1 is expected. Figures 5 and 6 present the obtained results. This package of measures reduces energy demand, achieving greater decreases compared with the previous case. In the current scenario, the quartile values of the hourly heating demand were reduced by 0.91 kWh for Q1, 11.18 kWh for Q2, and 25.18 kWh for Q3. These reductions translate to an average increase in savings of 23.59% in heating demand compared with Case 1. For cooling, the savings remained similar, with a slight increase of 0.67%.

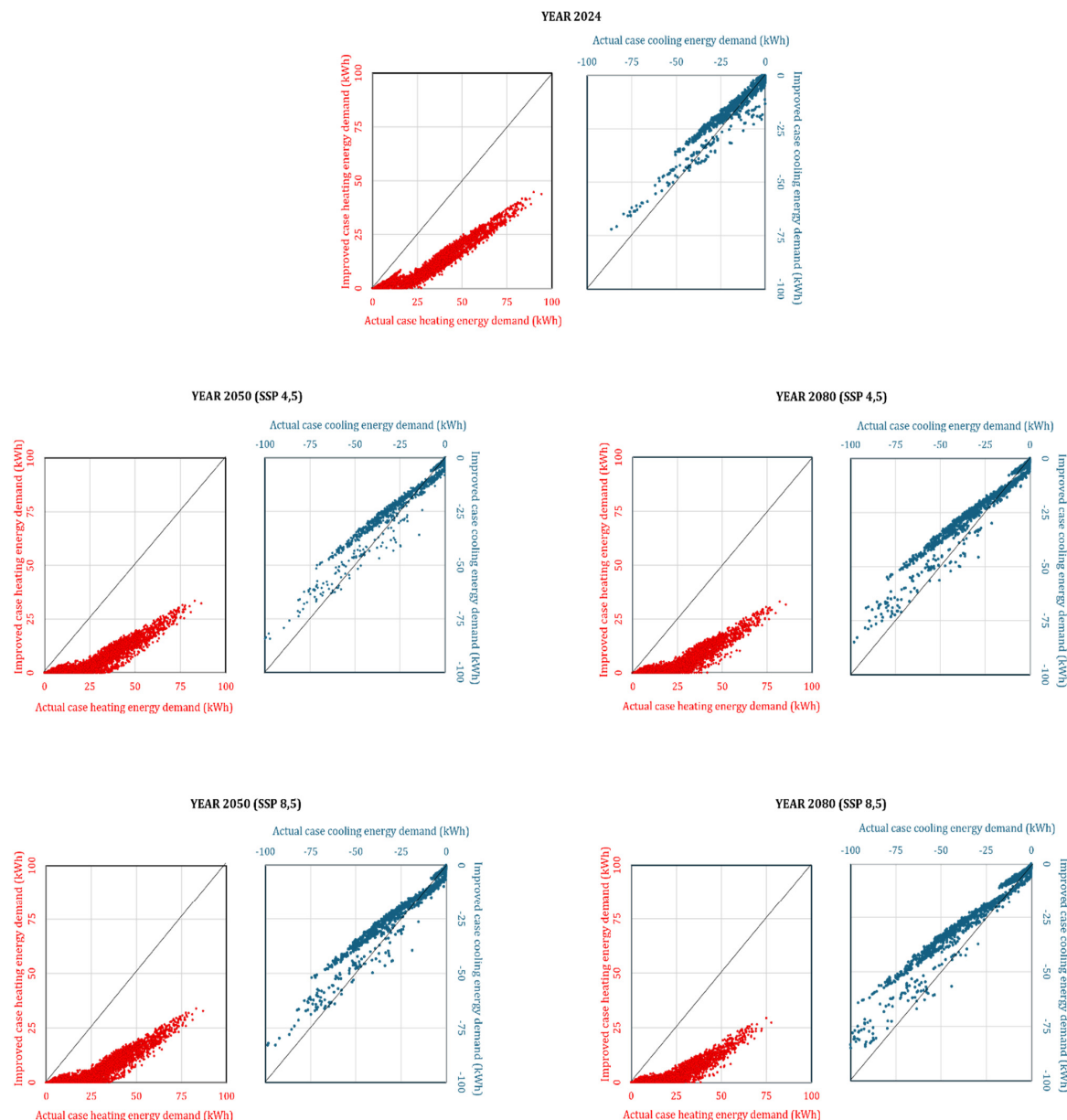


**Figure 5.** Scatter plot of the hourly heating and cooling energy demand achieved in Case 2 (window replacement and facade insulation).

Therefore, adding insulation effectively reduces the heating demand but has limited effectiveness for cooling. The analysis extends to the SSP scenarios, which project an increase in cooling demand but only slight improvements in savings compared with Case 1. Annual percentage savings for cooling increased by 1% compared with Case 1. Although the strategy's effectiveness for cooling demand remains limited, it achieves notable heating demand reductions of up to 83%.

In Case 3, the combination of window replacement, facade insulation, and roof insulation was analyzed. This is the most comprehensive envelope improvement framework proposed in the study. Figures 7 and 8 present the obtained results. Adding roof insulation does not change the trends observed in the previous cases. However, the energy savings achieved with this improvement are more pronounced: an annual savings of 9% for cooling and 74% for heating in the current scenario. In future scenarios, heating savings could increase to 90%, effectively eliminating heating energy consumption. For cooling, future savings could increase by up to 1% compared with the previous cases.

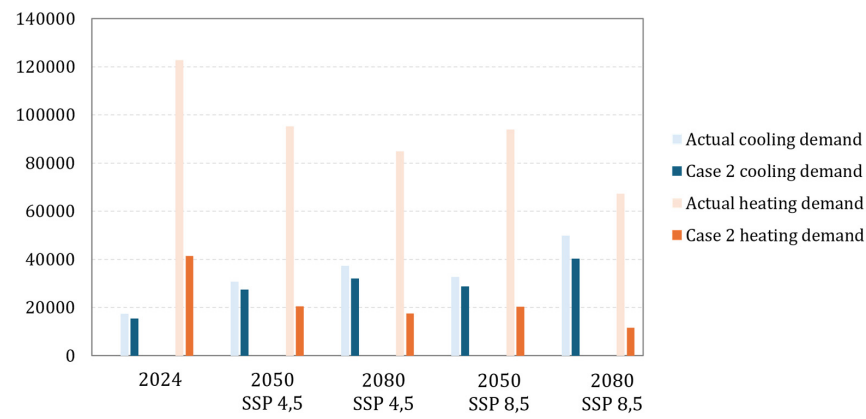


**Figure 6.** Total energy demand achieved in Case 2 (window replacement and facade insulation).

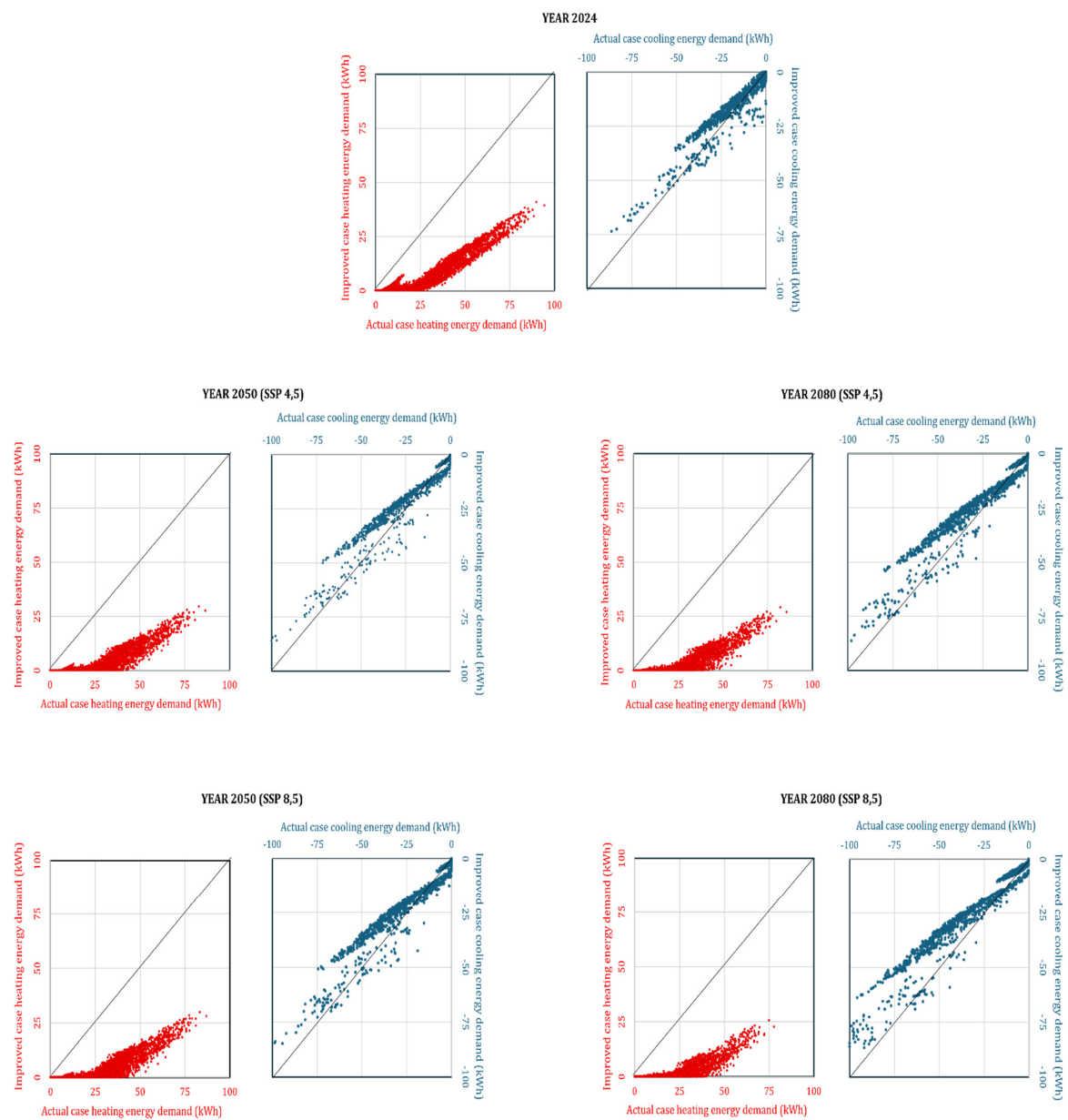


**Figure 7.** Scatter plot of the hourly heating and cooling energy demand achieved in Case 3 (window replacement, facade insulation, and roof insulation).

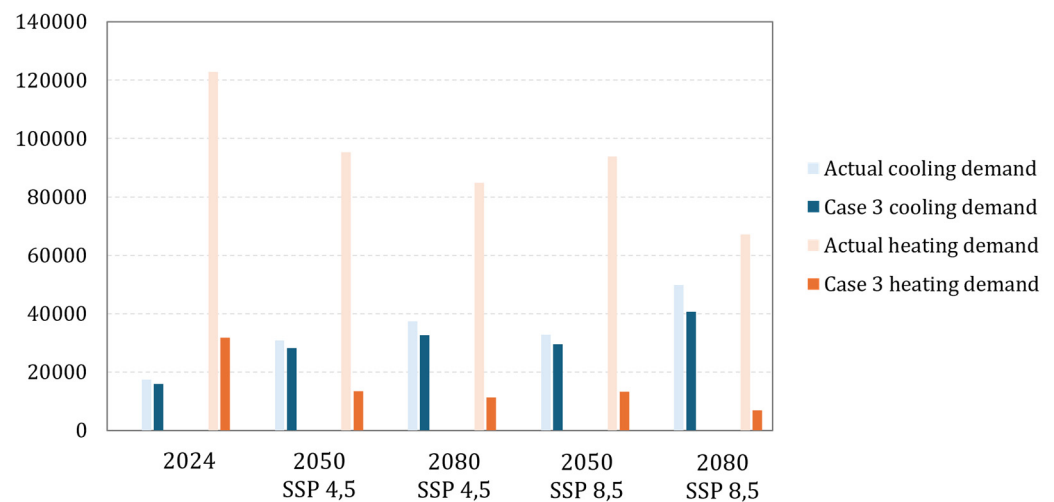


**Figure 8.** Total energy demand achieved with Case 3 (window replacement and insulation of facades and roofs).

This highlights the duality of the strategy: it is highly effective for heating but offers limited savings for cooling. Given the future trend under the scenarios—an increase in cooling demand and a decrease in heating demand—energy retrofit strategies must go beyond envelope improvements. Incorporating high-efficiency HVAC systems, self-consumption, and renewable energy sources (e.g., geothermal energy) might be critical. However, current budget constraints may limit the implementation of these measures in educational buildings.

A significant observation is the progressive decrease in the coefficient of determination between the hourly energy demand values of the current case and the improved case across the different retrofit measures. For heating, Case 1 values ranged from 88.4% to 97.4% for heating. In Case 2, they dropped to 78.1% to 93.1%. In Case 3, they declined further to 64.3% to 87.7%. This progressive reduction reflects a weaker association between current and improved values as the envelope retrofit becomes more comprehensive, primarily due to a higher concentration of instances with zero energy demand. This trend is not observed in the cooling demand, where the energy consumption remains high. Coefficients of determination range from 95.7% to 98.8% across all analyzed combinations.

These findings suggest that the energy performance of educational buildings cannot be fully optimized through envelope retrofitting strategies alone. While widely implemented in the Spanish built environment [41], these measures may have limited effectiveness in warm climate zones. Additionally, the results highlight the amplified impact of climate change under SSP scenarios compared with prior studies. Earlier research suggested that SRES or RCP scenarios could increase energy demand by 34% to 44% by 2050 for educational buildings [54]. However, this study shows that projected increases may be significantly higher under the new SSP framework. Specifically, for buildings with mixed uses, increases of up to 83% were observed.

Despite this, the analysis conducted in this study was not solely focused on the energy performance of the educational building. It also aimed to evaluate the level of thermal comfort achieved. This was particularly relevant given the building's typical summer operation, during which air conditioning is not used. This operational aspect may limit the payback periods for such improvements, as there are no cooling-related energy expenses. Therefore, the analysis was carried out during the summer months, considering both nighttime periods (residential use by teaching staff) and daytime periods (educational use). The results of the thermal comfort analysis are summarized in Tables 4 and 5.

**Table 4.** Percentage of daytime thermal comfort hours during the summer period.

| Case                             | Daytime Comfort (Hours) |          |          |          |          |
|----------------------------------|-------------------------|----------|----------|----------|----------|
|                                  | 2024                    | 2050—4,5 | 2080—4,5 | 2050—8,5 | 2080—8,5 |
| Actual building                  | 98.39                   | 96.54    | 93.09    | 94.12    | 88.13    |
| Case 1: windows                  | 100.00                  | 100.00   | 100.00   | 100.00   | 100.00   |
| Case 2: windows + facades        | 100.00                  | 100.00   | 100.00   | 100.00   | 100.00   |
| Case 3: windows + facades + roof | 100.00                  | 100.00   | 100.00   | 100.00   | 100.00   |

**Table 5.** Percentage of nighttime thermal comfort hours during the summer period.

| Case                            | Nighttime Comfort (%) |          |          |          |          |
|---------------------------------|-----------------------|----------|----------|----------|----------|
|                                 | 2024                  | 2050—4,5 | 2080—4,5 | 2050—8,5 | 2080—8,5 |
| Actual building                 | 70.00                 | 17.10    | 7.58     | 15.81    | 0.97     |
| Case 1: windows                 | 63.71                 | 12.90    | 5.16     | 12.42    | 0.32     |
| Case 2: windows + facades       | 66.61                 | 15.48    | 5.97     | 14.19    | 0.65     |
| Case 3: windows+ facades + roof | 70.16                 | 18.71    | 8.23     | 15.81    | 1.77     |

Regarding daytime hours, the effectiveness of the measures is evident across all the analyzed combinations. Even in buildings without any insulation improvements, values exceeding 80% were achieved by the end of the century. This advantage largely stems from the extended thermal comfort limits defined by the adaptive model in EN 16798-1:2019. The category used in this study is the most restrictive (category I), yet upper limits of up to 30.7 °C are accepted. In most cases, the operative temperature remained below this threshold, with no instance of  $t_{pma(out)}$  exceeding 30 °C. Adopting envelope improvements achieves 100% thermal comfort hours across all the considered scenarios. Although this is a clear advantage, these results do not account for the impact of high indoor temperatures during summer on children's cognitive performance. Elevated temperatures, even when within the thermal comfort range, could still affect children's intellectual performance. In such cases, air conditioning systems may be necessary, as most of the hourly temperature values exceeded 26 °C.

Regarding nighttime thermal comfort, Table 5 shows that in 2024, the case study achieved 70% of the nighttime hours as falling within the thermal comfort range. This situation changes drastically in the future scenario. Percentages drop to between 15.81% and 17.10% by 2050, and further decline to between 7.58% and 0.97% by 2080. By the end of the century, nearly all nighttime hours fall outside the thermal comfort range. Envelope improvement strategies do not significantly improve nighttime thermal comfort. In fact, both Case 1 and Case 2 worsen nighttime thermal comfort conditions due to a slight temperature increase, likely caused by the overheating of indoor spaces. In contrast, only Case 3, with roof insulation, improves nighttime comfort. This result is likely explained by the sleeping area being located on the top floor.

Slight improvements in nighttime thermal comfort during summer can be achieved. However, an in-depth analysis is required to precisely determine the optimal configuration of envelope improvements, as these measures may lead to overheating, which would negatively impact nighttime comfort. Future projections indicate a negative trend in nighttime comfort hours, necessitating the use of active systems to ensure suitable conditions for restful sleep. This issue is significant in the scientific literature, as no prior studies have directly explored how climate change impacts nighttime thermal comfort conditions. The limited studies available on this topic primarily focus on urban-scale analyses [55] or the operational patterns of mechanical systems [56]. Based on these findings, envelope improvement strategies alone are not an ideal solution for this challenge, especially given the climatic changes projected for the end of the century. They should also promote feasible,

and even minor, thermal upgrades that significantly improve the thermal performance of the building envelope [57]. Even so, a combination of passive and active solutions may be essential to tackle this issue effectively. A detailed analysis of the energy consumption curve would also be necessary to prevent any excessive costs associated with these measures.

## 5. Conclusions

This article presents an innovative approach by applying advanced Shared Socio-economic Pathway (SSP) climate scenarios to evaluate the effectiveness of passive energy retrofit strategies in educational buildings located in Mediterranean climates. The findings highlight the need to tailor energy retrofit interventions to specific climate projections, showing that the analyzed measures impact energy demand and thermal comfort differently across temporal scenarios. Notably, building envelope retrofitting reduces heating demand by up to 90% in future scenarios. Specifically, the analysis shows that in the current scenario, the combined interventions (window replacement, facade insulation, and roof insulation) result in annual savings of up to 74% for heating. Under SSP2–4.5 and SSP5–8.5 scenarios, heating savings could reach 90%, while cooling demand reductions range from 1% to 9%, as shown in the results section.

From a methodological perspective, the use of tools like DesignBuilder, combined with current and projected climate data, has proven to be an effective and reliable modeling tool for simulating complex scenarios and for producing accurate results on energy performance and thermal comfort evolution. The originality of this research study lies in its ability to identify not only the most effective measures in the current context but also to anticipate their performance under various climate projections. Comparing temporal horizons (2024, 2050, and 2080) under SSP scenarios provides a replicable framework for decision-making in other climatic and socioeconomic contexts.

The results demonstrate that, in the pilot case, envelope interventions such as window replacements, facade insulation, and roof insulation significantly reduce the energy demand. For instance, these combined measures yield annual savings of up to 9% for cooling and 74% for heating in the current scenario. These values have been thoroughly addressed and evaluated in the Results section, ensuring that the conclusions are directly aligned with the findings presented earlier. Therefore, the most effective measures identified in the analyzed cases include the integration of window replacements, facade insulation, and roof insulation.

Furthermore, as future climate scenarios project increases in cooling demand and decreases in heating demand, these measures remain central to mitigating these changes. Combining these strategies addresses the dual challenge of reducing heating demand while offering slight improvements in the cooling demand. The replicability of the model used in this study is made possible by its reliance on accessible data and standardized simulation methods, allowing the approach to be adapted to other climates and building types. This highlights the importance of tailoring approaches that integrate global data with localized adaptations, especially for building technical specifications, climate data, and user demands.

As potential avenues for future research stemming from this study, several emerging areas have been identified based on the application of the proposed model to this educational center in Granada. It is crucial to emphasize that these strategies impact both energy demand and the thermal comfort of occupants. Therefore, hybrid solutions combining passive measures with active systems will be essential to ensure optimal comfort, especially in contexts where high temperatures may negatively impact cognitive performance in educational environments.

Finally, this study contributes to the development of practical tools for architects and policymakers, providing a replicable analytical model to assess the feasibility and effectiveness of passive strategies in Mediterranean contexts. The findings can guide the design of targeted interventions to enhance energy efficiency while minimizing the environmental impact, aligning with European objectives for nearly-zero-energy buildings (nZEB) and supporting a transition toward climate-resilient educational infrastructure.

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