

Article

Energy Performance and Thermal Comfort in Madrid School Buildings Under Climate Change Scenarios

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Featured Application

The findings of this study can guide the design and prioritization of energy retrofitting strategies in existing school buildings. Public administrations, technical offices, and design teams can use simulated scenarios to evaluate the impact of passive and active measures—such as envelope insulation, solar control, and mechanical ventilation—under both current and future climate conditions. This approach is especially relevant for high-occupancy buildings in warm or temperate climates, where indoor comfort and energy efficiency must be carefully balanced.

Abstract

This study presents a detailed analysis of the energy performance and thermal comfort conditions in four existing school buildings located in Madrid, Spain. Dynamic simulations were conducted using TeKton3D—(iMventa Ingenieros, Málaga, Spain)- an open-source tool based on the EnergyPlus engine—to model four improvement scenarios: (I) current state, (II) envelope retrofitting with ETICS and high-performance glazing, (III) solar control strategies, and (IV) incorporation of mechanical ventilation with heat recovery. Each building was simulated under both current and projected 2050 climate conditions. The case studies were selected to represent different construction periods and urban contexts, including varying levels of exposure to the urban heat island effect. This approach allows the results to reflect the diversity of the existing school building stock and its different vulnerabilities to climate change. The results show that envelope retrofitting substantially reduces heating demand but may increase cooling needs, particularly under warmer future conditions. Solar control strategies effectively mitigate overheating, while mechanical ventilation with heat recovery contributes to improved comfort and overall efficiency. This study highlights the trade-offs between energy savings and indoor environmental quality, underlining the importance of integrated renovation measures. The study provides relevant data for decision-making in climate-resilient building renovation, aligned with EU goals for nearly zero and zero-emission buildings.

Keywords: school buildings; thermal comfort; energy performance; dynamic simulation; climate change; retrofit strategies; mechanical ventilation; passive design; overheating; TeKton3D; EnergyPlus



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1. Introduction

The operation of buildings accounts for about 30% of global final energy consumption and 26% of energy-related CO₂ emissions, including 8% direct emissions and 18% indirect

emissions from electricity and heat generation [1], 37% of total greenhouse gas (GHG) emissions [2], and more than half of final electricity demand [1].

In this context, the built environment stands out as one of the most critical sectors in which to take action. That is why many countries are increasingly focused on reducing the energy demand of the existing building stock and on promoting innovative solutions that lower consumption while preserving indoor comfort conditions. The European Union is no exception. According to the latest Energy Efficiency Directive (2024), all buildings—both new and existing—must be transformed into zero-emission buildings by 2050 [3]. And yet, under the pressing reality of climate change, the challenge becomes even more urgent. It calls for more ambitious measures that go beyond conventional approaches to limiting energy demand. Recent studies have reported a growing number of hours during which indoor conditions fall outside thermal comfort ranges [4], especially due to overheating [5], which in turn is linked to increased morbidity [6] and rising energy demand for cooling—up to 4.6% in office buildings in China [7].

2. Literature Review

2.1. School Buildings and Comfort Conditions

Among the building types most critical in the context of climate change adaptation, schools play a particularly significant role. This is largely because children are among the most vulnerable populations when it comes to rising temperatures—their thermoregulation mechanisms are not yet fully developed [8]. As a result, they face a higher risk of developing heat-related health issues, such as kidney and respiratory problems, electrolyte imbalances, or fever during heatwaves and abrupt temperature shifts [9]. Despite this vulnerability, most school buildings still lack basic energy efficiency measures [10].

In this context, several researchers in Turkey warn that energy consumption in buildings could potentially double in the coming decades [11]. This concern has led to a growing number of studies focused on the implementation of thermal insulation as a key strategy to reduce energy demand. For example, in Jordan, Ali et al. (2019) [12] reported reductions of up to 20.3% in cooling demand and 28% in heating demand following insulation upgrades. Along these lines, recent studies in school buildings in Serbia show that the incorporation of thermal insulation can reduce energy consumption by up to 152 kWh/m² per year and improve energy efficiency by between 48% and 56% [13]. In Argentina, retrofitting of the building envelope with thermal insulation in a school led to a reduction in heating consumption of up to 55% [14].

In most European countries, energy renovation interventions in public buildings, including schools, tend to focus primarily on passive envelope improvements, such as adding thermal insulation to façades or roofs and replacing windows. While these measures are effective in reducing heating demand in cold climates, they are often implemented in isolation, without incorporating additional strategies such as solar control, mechanical ventilation, or active indoor comfort management. This limitation becomes particularly critical in the context of climate change, where improving airtightness alone may exacerbate overheating problems and compromise indoor environmental quality. According to a recent analysis by the Bruegel think tank, based on data from the European Environment Agency (EEA) and the United Nations Framework Convention on Climate Change (UNFCCC), only 0.3% of non-residential buildings in the European Union underwent a deep renovation—defined as achieving at least 60% energy savings—between 2016 and 2020 [15]. This figure is consistent with data from the European Climate Neutrality Observatory, which also reports a deep renovation rate of 0.3% for non-residential buildings, highlighting the limited adoption of comprehensive retrofit strategies despite the EU's climate neutrality commitments for 2050 [16].

Even in the pursuit of improved building envelopes, several studies have explored the integration of phase change materials (PCMs) as a strategy to enhance indoor comfort conditions [17]. However, evidence suggests that these solutions—particularly in warm climates and under climate change scenarios—are not always effective and may, in fact, worsen overheating issues [18]. Pyrgou et al. (2017) [19] found that during extreme heat events, insulated buildings could experience indoor temperatures up to three times higher than those without insulation, highlighting the complexity of passive solutions in climate-vulnerable regions.

Considering these findings, several researchers have proposed alternative mitigation strategies—particularly solar radiation control measures. These approaches are especially relevant in warm-climate countries, where solar gains have a significant impact on the building's overall energy performance. In this regard, a study conducted in Nigeria shows that the incorporation of fixed external shading combined with low emissivity glazing in a school building led to a 16% reduction in energy consumption, a 56 kWh/m² decrease in cooling demand, and a 44% reduction in thermal discomfort hours compared to the original building without optimization measures [20]. A study carried out in the south of Spain shows that the incorporation of external solar protections, such as horizontal slats, canopies, and vegetation screens, allows for a reduction of cooling energy demand in school buildings by up to 6.7% and heating demand by 5.2% when applied in combination on the reference building model, without additional improvements to the envelope [21].

Finally, another strategy explored in various studies is passive ventilation, which is aimed at preventing indoor overheating [22,23]. A study conducted in school buildings in southern Spain found that adequate natural ventilation (8–12 ACH) can reduce summer thermal discomfort by 18–32%, depending on climatic location [24]; however, the analysis did not include mechanical ventilation systems or heat recovery. However, when mechanical ventilation with heat recovery is incorporated, studies also report benefits in terms of energy efficiency: In a practical case in an Italian school, this solution led to a 32% reduction in heating energy consumption compared to the regulatory scenario with natural ventilation, due to a heat recovery efficiency of 90% [25]. Moreover, improvements in thermal comfort have been observed, with indoor temperatures remaining around 21–23 °C and showing less variability compared to natural ventilation, which caused occasional drops down to 18.9 °C during window opening [26].

Regarding these strategies, several authors emphasize the importance of conducting detailed studies that take heatwave events into account [27].

2.2. Energy Saving Measures in School Buildings

Several studies emphasize the need to adopt combined passive measures specifically tailored to the adaptation of school buildings [28].

In this regard, the literature highlights the need for holistic approaches that span from envelope improvements to the integration of efficient active systems [29] and even smart management technologies (VERYSCHOOL). In recent years, these strategies have increasingly included the assessment of the environmental impact associated with each intervention [30], and in some cases, the implementation of educational initiatives aimed at raising awareness about the issue (SchoolVentCool, 2012). In this line, a recent study on English school stock analyses the combined effect of thermal envelope improvement and various passive and active adaptation strategies. Based on the indicator of Cognitive Performance Loss (CPL), it is confirmed that insulation can generate counterproductive effects if not accompanied by complementary measures. Among these, mechanical ventilation, external shading, and especially active cooling with a set-point temperature of 21 °C stand

out, which allows the CPL to be reduced to low levels (4.4%), although with a significant increase in energy demand (up to 75 kWh/m² in warm regions) [31].

In this context, however, there is no unified criterion regarding the effect that climate change may have on the behavior of buildings and the suitability of certain energy retrofit strategies. This is precisely the focus of the present research. To this end, four case study buildings will be analyzed to evaluate the influence of climate change and the different improvement options that could be proposed to enhance their energy performance.

3. Research Questions

Based on the literature review and the identified research gap, this study aims to address the following research questions:

1. How do school buildings in Madrid—characterized by high internal loads, limited HVAC systems (mainly heating designed for winter conditions), and a vulnerable user population—perform in terms of energy demand and thermal comfort under current climate conditions? And, consequently, do these buildings require a specific retrofit approach, different from standard guidelines, that is adapted to their particularities?
2. How does envelope retrofitting—especially interventions on windows—affect the removal of uncontrolled ventilation typical of the original construction context when applying standard envelope rehabilitation criteria, and what specific scope should such measures have in the case of school buildings?
3. How will the energy and comfort performance indicators of the analyzed schools evolve under projected climate change scenarios for 2050?
4. What is the relative effectiveness of different retrofit strategies—improving thermal envelopes, solar control measures, and mechanical ventilation with heat recovery—in reducing energy demand and mitigating discomfort?
5. What trade-offs emerge between energy efficiency and thermal comfort when applying these retrofit strategies, and how can they inform balanced renovation policies for school buildings?
6. How can the results of this study inform decision-making in renovation policies and regulatory adaptation towards nearly zero-energy and zero-emission school buildings in the European framework?

4. Materials and Methods

Four school buildings located in Madrid and its metropolitan area were selected, each representative of different construction periods and regulatory contexts related to energy efficiency.

This research was carried out within the framework of the project Lime4Health (PID2021-123023OA-I00), funded by MCIN/AEI/10.13039/501100011033 and FEDER “Una manera de hacer Europa”. The selection of the four schools was carried out according to two main criteria: (i) their location with respect to the urban heat island (UHI) of Madrid and (ii) their different construction periods and regulatory contexts. This approach ensures that the case studies reflect both the diversity of building typologies in metropolitan areas and their varying exposure to UHI intensity.

- S1 (1968): located in the consolidated neighborhood west of Madrid, close to the largest green space in the city and 40 m from a highway. It is located in a medium-density residential area developed in the 1960s, following garden city principles. Despite nearby green masses, it is within UHI zones, with summer nocturnal increases of 2–3 °C and winter differences of +1 °C.
- S2 (1970): situated in the central district, in proximity to the ring road and a park, at the southeast of the city, in a dense area of high-rise blocks and traffic corridors. It is

subject to stronger UHI effects, with nocturnal increases of 4–5 °C in summer and +2 to +3 °C in winter.

- S3 (2012): located in a new municipality on the east outskirts of Madrid, within a low-medium-density new residential development. It lies in UHI zones, with +2–3 °C in summer and +1 °C in winter compared to the periphery.
- S4 (2001): located in a new neighborhood at the north of Madrid, a new residential area of the 2000s within a new low-density urban structure development in north Madrid, with surrounding open green spaces, yet still affected by UHI, with +2–3 °C in summer and +1–2 °C in winter.

The constructive and energy-related features of the school buildings are summarized in Table 1, which highlights notable differences between the facilities—even among those built in similar periods. The energy simulations incorporated the actual heating systems present in each school, all of which are based on hot-water radiator systems.

Table 1. Selected buildings.

School	Location	Year of Construction	Applicable Regulation	Thermal Requirement—Walls	Thermal Requirement—Roofs	Thermal Requirement—Windows
S1	Southwest	1968	-	-	-	-
S2	East	1996 ¹	NBE-CT79 [32]	1.40 W/m ² K	0.90 W/m ² K	-
S3	Extra radio	2012	CTE-DB-HE 2006 [33]	0.66 W/m ² K	0.38 W/m ² K	3.5 W/m ² K
S4	North	2001	NBE-CT79 [32]	1.40 W/m ² K	0.90 W/m ² K	-

¹ This building was renovated in 2023 by improving its thermal envelope.

- S1, built in 1968, is equipped with full-height vertical radiators in each classroom, with no individual control, and a conventional gas boiler for heat generation. Domestic hot water (DHW) for the kitchen is supplied through electric water heaters.
- S2, recently renovated, maintains a gas wall-mounted boiler and hot-water radiator system, but does not include any mechanical ventilation system.
- S3, constructed in 2012, features aluminum convector radiators supplied by two high-efficiency gas condensing boilers, along with a mechanical ventilation system with heat recovery, controlled by CO₂, temperature, and humidity sensors.
- S4 is heated by a hot-water radiator system powered by a natural gas boiler and lacks mechanical ventilation.

None of the schools are equipped with active cooling systems, so the simulation model considered only the operation of the heating systems during school occupancy periods. Regarding lighting, standard values for power and efficiency were applied according to the type of luminaire installed in each building: fluorescent fixtures were assumed for Schools S1, S2, and S4, while LED lighting was considered in School S3. The geometric ratios and envelope construction details of the case study schools are summarized in Table 2.

The energy simulations in this study were carried out using TeKton3D TK-CEEP, developed by iMventa Ingenieros (Málaga, Spain). This is one of the officially recognized tools in Spain for the energy performance certification of buildings, in accordance with the framework established by the Technical Building Code (CTE) and the procedure of the Spanish Ministry for the Ecological Transition and the Demographic Challenge. TeKton3D uses EnergyPlus (version 8.9.0, U.S. Department of Energy, Washington, DC, USA) as its simulation engine, which is internationally regarded as a benchmark for dynamic energy modeling. In addition to its official status, TeKton3D is currently accepted as a valid tool for assessing energy performance in the context of public funding programs

for energy renovation (such as those financed by Next Generation EU funds), further supporting its suitability for modeling energy improvement scenarios from an applied and operational perspective. TeKton3D TK-CEEP was selected as a free tool that incorporates the EnergyPlus calculation engine, like other recognized options such as CYPETHERM HE Plus or SG SAVE. Among these, TeKton was chosen for its integrated 3D modeling environment, which allows for a precise definition of geometry and thermal zoning without the need for external software. This tool has been used in previous research to analyze the energy performance of buildings, demonstrating the validity of the procedure [34].

Table 2. Geometric ratios and envelope construction data for school case studies. Own elaboration.

School	Facade Construction Solution	Roof Construction Solution	Construction Detail—Openings	Volume-To-Surface Ratio (V/A)	Window-To-Wall Ratio (WWR)
S1	1/2 brick facade with double hollow brick interior leaf. No thermal insulation. $U_F = 1.49 \text{ W/m}^2 \text{ K}$	Flat roof. Exposed metal profiles and particle board. No thermal insulation. $U_R = 3.09 \text{ W/m}^2 \text{ K}$	Double glazing 4/6/4 Aluminum frames Class 1 $U_W = 3.78 \text{ W/m}^2 \text{ K}$	1.29	19.52%
S2	1/2 brick facade with double hollow brick interior leaf. External thermal insulation system (ETICS) with 9 EPS $U_F = 0.31 \text{ W/m}^2 \text{ K}$	Gable roof. Ceramic tile finish. 3 cm of extruded polystyrene (XPS) insulation $U_R = 0.83 \text{ W/m}^2 \text{ K}$	Low-emissivity double glazing 3 + 3/16/4 + 4 PVC frames Class 4 $U_W = 1.48 \text{ W/m}^2 \text{ K}$	2.69	19.23%
S3	1/2 brick facade with double hollow brick interior leaf. 4 cm of expanded polystyrene (EPS) $U_F = 0.63 \text{ W/m}^2 \text{ K}$	Flat roof. Metal sheet finish. 7 cm of extruded polystyrene (XPS) insulation $U_R = 0.37 \text{ W/m}^2 \text{ K}$	Double glazing 4/9/6 Aluminum frames Class 2 $U_W = 2.48 \text{ W/m}^2 \text{ K}$	1.80	31.99%
S4	1/2 brick facade with double hollow brick interior leaf. No thermal insulation $U_F = 1.37 \text{ W/m}^2 \text{ K}$	Flat roof. Gravel finish. 2 cm of extruded polystyrene (XPS) insulation $U_R = 0.83 \text{ W/m}^2 \text{ K}$	Double glazing 4/9/6 Aluminum frames Class 2 $U_W = 2.48 \text{ W/m}^2 \text{ K}$	2.4	22.18%

In this study, the energy models of the four school buildings were not calibrated with real consumption data, since the objective is not to precisely reproduce their current energy behavior, but rather to consistently compare different improvement scenarios using an official, government-approved tool, and to evaluate their projected performance in the year 2050. Thus, the study focuses on analyzing relative trends and the potential impact of various intervention strategies (building envelope upgrades, ventilation systems, solar shading, etc.) on energy performance within a normative and technical framework aligned with current requirements for energy assessment and eligibility for public funding. The simulation models of the four school buildings are shown in Figure 1.

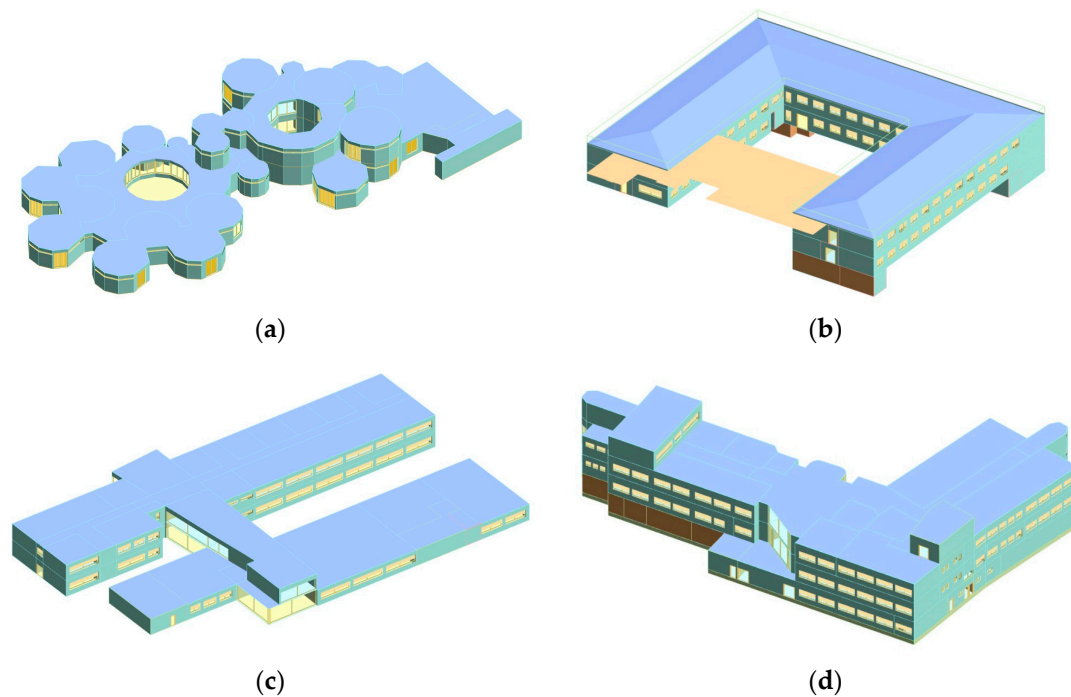


Figure 1. Images of the simulations of the school buildings under study using the TeKton3D TK-CEEP tool. (a) S1, (b) S2, (c) S3, and (d) S4. Own elaboration.

Both the current state of the buildings and their performance under the four progressive retrofit scenarios have been analyzed. Each scenario includes specific improvement measures related to the building envelope, solar control systems, and mechanical ventilation with heat recovery. Simulations were carried out under present climate conditions, as well as under a projected climate scenario for the year 2050, using climate data generated with the CCweatherGen software developed by the University of Southampton UK; University of Southampton, (version 1.1.2).

For each building, heating and cooling demands were extracted, along with the number of unmet hours. According to the definition used by the simulation tool TeKton3D (version 1.8.6, iMventa Ingenieros S.L., Málaga, Spain) and the Spanish Technical Building Code, CTE DB-HE 2019 (Ministry of Transport, Mobility and Urban Agenda, Government of Spain), unmet hours are calculated during the defined occupied hours and represent the sum of all habitable spaces that fall outside the setpoint range by more than ± 1 °C—either due to overheating in summer or underheating in winter. For example, if 15 spaces are simultaneously out of setpoint in a given time slot, this is counted as 15 unmet hours. Therefore, the indicator should be understood as an aggregated whole-building metric of thermal comfort compliance, and not as the exact number of teaching hours affected. This explains why the total values may exceed the number of annual occupied hours, while remaining consistent with the TeKton3D methodology and enabling objective comparison across buildings and retrofit scenarios.

It should be noted that the models were not calibrated with measured consumption data, since the study focuses on the energy demand of the buildings—using official software for building energy performance—rather than on a direct comparison with their actual energy use. In any case, ongoing research with other software has been performed in order to compare those results with the ones achieved with calibrated models with HVAC systems. Then, the aim of this research is to assess the passive behavior of schools under current and future climate conditions, with particular emphasis on cooling demand, for which no active systems are currently installed in any of the case studies. Actual consumption values

would strongly depend on the performance and operation of HVAC equipment, which are not the subject of this research.

4.1. Proposed Simulation Scenarios

Four situations were modeled: the current state of each building, which served as the baseline, and three retrofit scenarios focused on the building envelope, passive systems, and active systems.

In the Current Situation, Scenario II, and Scenario III, no specific ventilation system was defined. The simulations account for uncontrolled natural ventilation, automatically assigned by the software according to the constructive solution of each building and the improvements applied in each scenario (i.e., higher airtightness is assumed when insulation levels increase). In Scenario IV, a mechanical ventilation system with heat recovery (75% efficiency, automatic bypass) was added, operating during school occupancy hours (8:00–17:00), in accordance with Spanish regulations (CTE and RITE).

4.1.1. Current Situation

This scenario analyzes the current performance of the buildings, including their construction systems, HVAC installations, and boundary conditions. It also considers various improvement strategies aimed at reducing the number of hours of thermal discomfort indoors and discusses potential alternative interventions. Given the significant impact of ventilation on energy performance, the following assumptions were made based on on-site observations and real-condition measurements:

- School S1: No thermal insulation, conventional aluminum window frames, and double hollow brick façade; airtightness class 1 ($50 \text{ m}^3/\text{h}\cdot\text{m}^2$).
- School S2: In this scenario, this school was simulated disregarding the thermal envelope improvement carried out in 2023, in order to compare the values obtained with those of the other schools included in the study. Therefore, its construction solutions prior to the 2023 intervention were considered: no façade insulation, 3 cm of XPS on the roof, and class 2 windows ($27 \text{ m}^3/\text{h}\cdot\text{m}^2$).
- School S3: Façade with 4 cm of thermal insulation and aluminum frames; airtightness class 2 ($27 \text{ m}^3/\text{h}\cdot\text{m}^2$).
- School S4: Façade with no thermal insulation and aluminum window frames; airtightness class 2 ($27 \text{ m}^3/\text{h}\cdot\text{m}^2$).

4.1.2. Scenario II: Improvement of the Thermal Envelope of the Buildings

This scenario focuses on retrofitting of the building envelope, including the application of ETICS systems and the replacement of windows with high-performance glazing, in order to reduce heating demand and improve thermal insulation. This scenario considers a set of measures commonly implemented in interventions aimed at reducing energy demand, in line with the requirements established by European building renovation programs. These programs typically require a minimum reduction of 30% in the building's overall non-renewable primary energy consumption, as outlined in the Spanish Urban Agenda [35].

Since one of the analyzed buildings (School S2) has already undergone an energy retrofit under one of these programs, the remaining cases are simulated by applying the same set of improvements implemented in that school. Specifically, the scenario assumes the installation of an external thermal insulation composite system (ETICS) with 9 cm of expanded polystyrene, along with the replacement of existing windows by low-emissivity double-glazed units with PVC frames, achieving air permeability class 4 ($3 \text{ m}^3/\text{h}\cdot\text{m}^2$ in glazed openings). These measures have been applied in the simulation of all buildings, including School S2, which already features these envelope characteristics in its current state.

4.1.3. Scenario III: Improvement and Installation of Passive Systems on the Thermal Envelope

This scenario is specifically focused on reducing cooling demand through the installation of external solar control measures such as shading devices and other passive strategies applied to the building envelope. Given the global trend toward rising temperatures, various strategies have been proposed to reduce the energy demand associated with summer cooling. In this scenario, two complementary measures were considered:

- The reduction in the solar factor of glazing, from a typical value of 0.60 (standard double glazing) to 0.35. The choice of 0.35 as the solar factor is based on a review of previous studies analyzing the energy performance of buildings through simulations using solar control glazing. These studies employ glazing with solar factor values ranging from 0.27 [36] to 0.45 [37], depending on the type and activation state of the glass. Within this range, the value of 0.35 [20] is adopted as representative, as it matches the value used in at least one previous study and lies in the middle of the range, reasonably reflecting the behavior of the advanced glazing solutions currently available.
- Solar control through external devices: operable louvers (horizontal on south-facing façades and vertical on west-facing ones [20]) and a fixed horizontal overhang of 1 m above south-facing windows in order to more effectively block incident solar radiation.

4.1.4. Scenario IV: Improvement of the Active Systems of the Buildings

This scenario considers the incorporation of mechanical ventilation with heat recovery, representing an improvement of the active systems to enhance energy efficiency and indoor comfort. As noted in the state-of-the-art section, natural ventilation is considered a passive strategy, while mechanical ventilation—since it only involves fan operation without any thermal energy input—can be regarded as a low-impact active strategy. The latter is increasingly being adopted internationally as a means of mitigating indoor overheating in buildings. In this scenario, the implementation of a mechanical ventilation system is evaluated—currently present only in School S3. In all previous scenarios, ventilation was considered uncontrolled, i.e., solely the result of air infiltration through the building envelope, depending on its permeability. While reducing uncontrolled ventilation improves energy efficiency, it may also lead to poor indoor air quality and increased overheating if not paired with an appropriate ventilation strategy.

Therefore, this scenario introduces a mechanical ventilation system with heat recovery (efficiency of 73%), in compliance with the minimum thermal efficiency set by European ecodesign regulations (Commission Delegated Regulation (EU) No 1254/2014) [38], and an automatic bypass function, which disables heat recovery when outdoor conditions are favorable—such as during cool spring or summer nights. This allows for direct ventilation without preheating, promoting the dissipation of accumulated internal heat and enhancing thermal comfort in high-occupancy environments like classrooms. The system operates only during school hours (Monday to Friday, 8:00 AM to 5:00 PM), and a reduction in uncontrolled air infiltration is also assumed, reflecting the improved airtightness of the envelope.

4.2. Scenarios Within the Future Climate Context

All the scenarios described above were simulated not only under current climate conditions but also within a future climate context (2050) in order to assess the combined effects of building retrofits and climate change projections. Following the definition of the simulation scenarios—current state, standard envelope upgrade (Scenario II), targeted cooling-oriented improvement (Scenario III), and integration of mechanical ventilation

with heat recovery (Scenario IV)—the applicability and effectiveness of these measures were further assessed within a projected future climate context. For this purpose, a climate projection for the year 2050 was incorporated into the modeling. As previously described, the CCWeatherGen tool developed by the University of Southampton was used to generate climate files suitable for building performance simulation [39]. This tool has been widely applied in previous research [40–42], demonstrating its reliability and suitability for the intended purpose: to comparatively evaluate, across the selected case studies, the energy performance of school buildings and the extent to which the strategies proposed today can withstand scenarios characterized by higher outdoor temperatures and increased seasonal thermal stress.

The baseline dataset corresponds to Spanish climatic zone D3 (Madrid metropolitan area, 40.68° N, −4.13° E, 667 m a.s.l.), as defined in the Spanish Technical Building Code (CTE 2016). Hourly records for the reference year (2001) were modified to reflect the projected conditions for 2050, including adjustments to mean monthly temperatures, diurnal ranges, humidity, and solar radiation. The resulting file (D3_peninsula.epw) was produced in TeKton3D and used in all simulations. The default configuration of CCWeatherGen is based on the SRES A2 scenario (IPCC AR4), which represents a medium-to-high emissions pathway broadly comparable to RCP 8.5 in the more recent IPCC assessments. According to this projection, the average annual dry-bulb temperature reaches approximately 17.1 °C, with summer peaks up to 43 °C and winter minima around 1 °C. Compared with current reference datasets for Madrid (mean annual temperature ~14–15 °C and historical maxima around 39–40 °C), this implies an increase of about 2–3 °C in average conditions and more than 3 °C in extreme summer peaks. These increments are consistent with IPCC medium-to-high emissions pathways and provide a robust basis for evaluating overheating risks and energy performance in school buildings under climate change.

Simulations under future climate conditions make it possible to assess the risk of overheating, the expected increase in cooling demand, and the potential loss of effectiveness of retrofit measures when exposed to more demanding climatic conditions during warm periods.

5. Results

5.1. Current Situation

In the current state, the energy performance of the four school buildings shows considerable variability, directly linked to their geometric and construction characteristics. As illustrated in Figure 2, heating demand ranges widely, from 36.01 kWh/m²·year in S2 to 201.56 kWh/m²·year in S1, revealing substantial differences in thermal retention capacity.

In the current state analysis, the shape factor (A/V ratio) was identified as a key variable influencing the energy demand of the case study buildings. Schools with a more compact geometry (lower A/V ratio) tend to present lower heating and cooling demands, while those with a higher exposed surface relative to their volume are more sensitive to external temperature variations and solar gains. This parameter, together with other building characteristics such as construction period, glazing ratio, and ventilation strategy, helps explain the differences observed among the four case studies. S2 has the highest compactness ratio in the group ($V/A = 2.69$), meaning a smaller exposed surface area relative to usable volume and therefore reduced thermal losses. Its low window-to-wall ratio (19.23%) further limits transmission losses through the glazing. These features explain why, even without significant thermal insulation, its heating demand is the lowest. At the opposite extreme, S1 has the lowest compactness ratio ($V/A = 1.29$), which increases the exposed surface area and amplifies energy losses through uninsulated walls and low-performance windows (Class 1). Although its window-to-wall ratio is almost identical to

S2's (19.5%), the combination of low compactness and high air permeability explains why its heating demand is nearly six times higher.

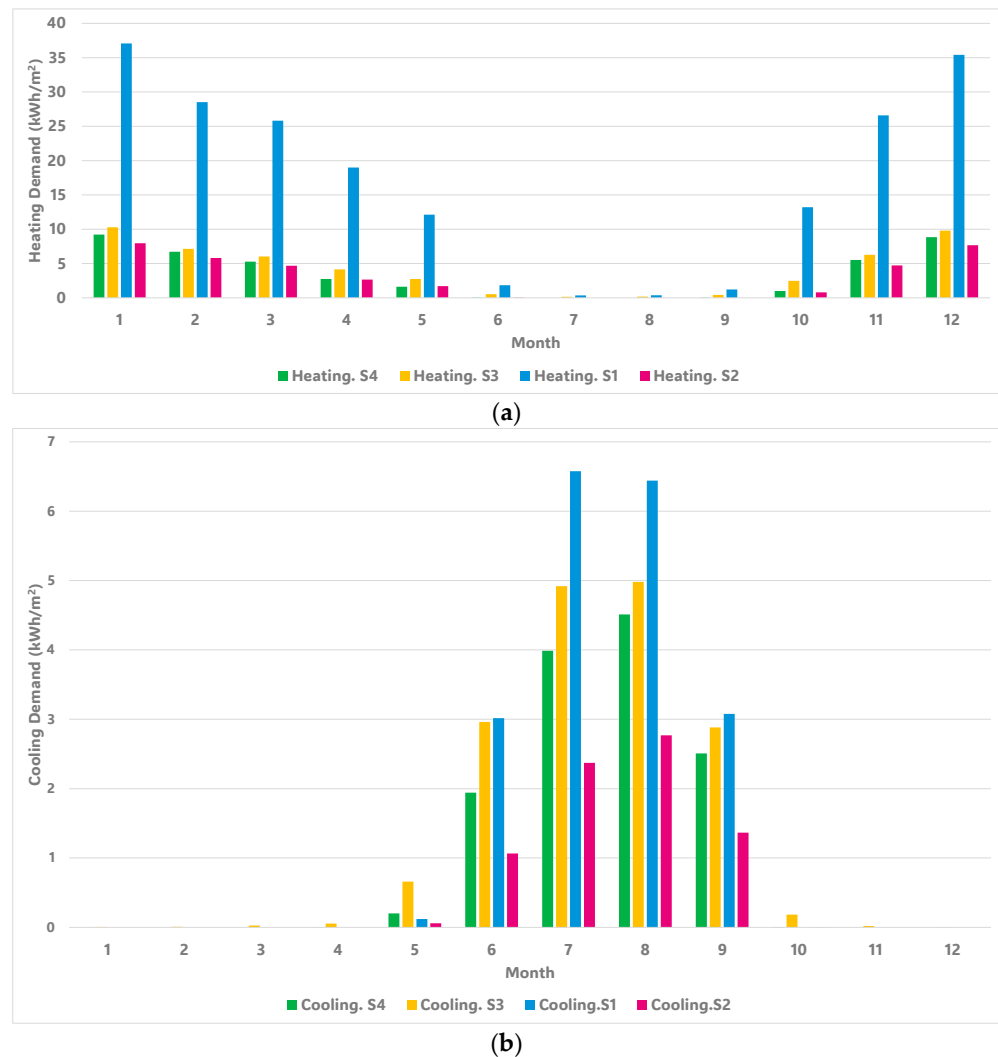


Figure 2. Monthly heating (a) and cooling (b) demand for each of the four school buildings in their current state. Own elaboration.

In an intermediate position is S4 ($V/A = 2.4$; $WWR = 22.18\%$), with uninsulated enclosures and aluminum frames. Its relatively high compactness helps keep its heating demand to $40.97 \text{ kWh/m}^2\cdot\text{year}$, although the slightly higher percentage of glazing compared to S1 and S2 penalizes its performance in cooling.

S3 ($V/A = 1.8$; $WWR = 31.9\%$) has a better envelope than S1 and S4, with partial insulation and more airtight windows, resulting in an intermediate heating demand ($50.23 \text{ kWh/m}^2\cdot\text{year}$). However, its high glazing ratio—the highest in the group—together with large windows in common areas, significantly increases unwanted solar gains. This leads to the second-highest cooling demand ($16.70 \text{ kWh/m}^2\cdot\text{year}$) and one of the highest numbers of hours out of setpoint, along with S4 ($34,432 \text{ h}$), despite having mechanical ventilation.

Regarding cooling, S1, despite its poor envelope, records the lowest cooling demand ($19.23 \text{ kWh/m}^2\cdot\text{year}$) and the fewest hours out of setpoint (8968 h). This performance is explained by its low glazing ratio and high air permeability, which favors a degree of uncontrolled natural ventilation and limits overheating. Conversely, S4, with a 22.18% glazing ratio and no solar control, shows the highest cooling demand ($13.15 \text{ kWh/m}^2\cdot\text{year}$).

and one of the higher number of hours out of setpoint (34,198 h), exacerbated by intensive use and the absence of mechanical ventilation.

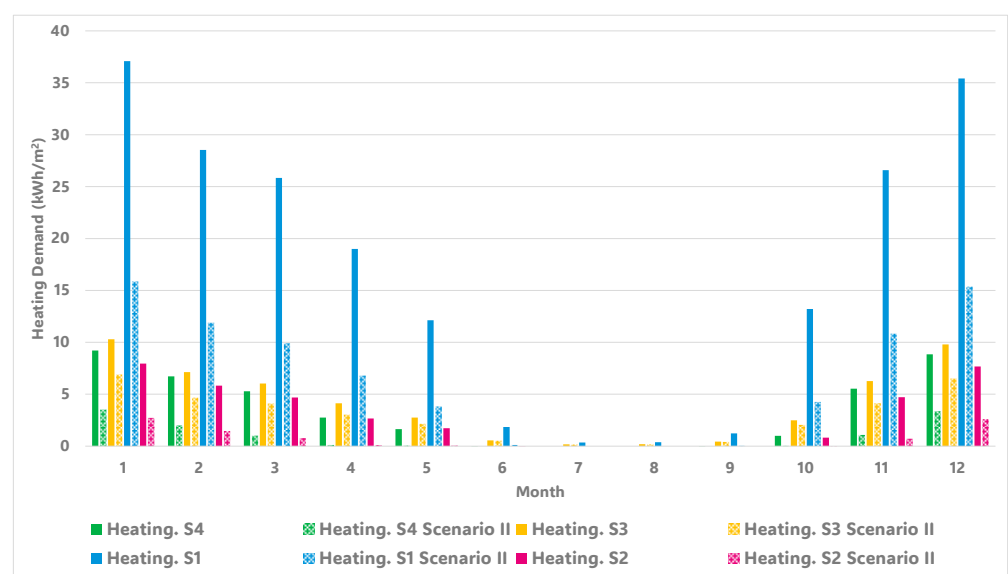
Overall, this scenario highlights the systemic vulnerability of schools to summer overheating, especially in the absence of mechanical cooling systems. The findings point to an urgent need for integrated design strategies that go beyond winter-focused thermal retrofits and address thermal resilience in summer, particularly in the face of climate change.

5.2. Scenario II: Improvement of the Thermal Envelope of the Buildings

The implementation of passive improvement measures on the building envelope—such as the addition of an ETICS system with 9 cm of expanded polystyrene and the replacement of windows with high-performance components (low-emissivity double glazing and PVC frames with Class 4 airtightness)—leads to significant reductions in heating demand across all four school buildings analyzed. The results of Scenario II show a widespread reduction in heating demand (Figure 3), with savings ranging from 30% to 77% compared to the current state (Table 3).

The greatest impact is observed in School S2, where heating demand drops from 36.01 to 8.41 kWh/m²·year, representing a 76.6% improvement. Notable reductions are also seen in S4, which lowers its heating consumption by 72.9% (from 40.97 to 11.12 kWh/m²·year), and in S1, which—despite starting from a very poor envelope—achieves a 60.9% decrease, from 201.56 to 78.81 kWh/m²·year. The smallest relative savings occur in S3, with a reduction of 30.9%, which is consistent with its already more efficient initial construction.

However, the improvement of the envelope does not have the same effect on passive performance regarding cooling demand. Rather than decreasing, cooling demands increased in all buildings, with rises between 42% and 49% in S3, S4, and S2. Only S1 shows a slight reduction of 15.4% (from 19.23 to 16.26 kWh/m²·year), likely due to its limited glazed surface and previously high permeability, which allowed some degree of uncontrolled natural ventilation. This increase in cooling loads is attributed to the fact that envelope improvements also reduce heat losses during warmer periods, hindering internal heat dissipation, especially in buildings with low thermal inertia or large unshaded glazed areas. This is particularly evident in S3, where cooling demand rises from 16.70 to 23.73 kWh/m²·year (+42.1%).



(a)

Figure 3. Cont.

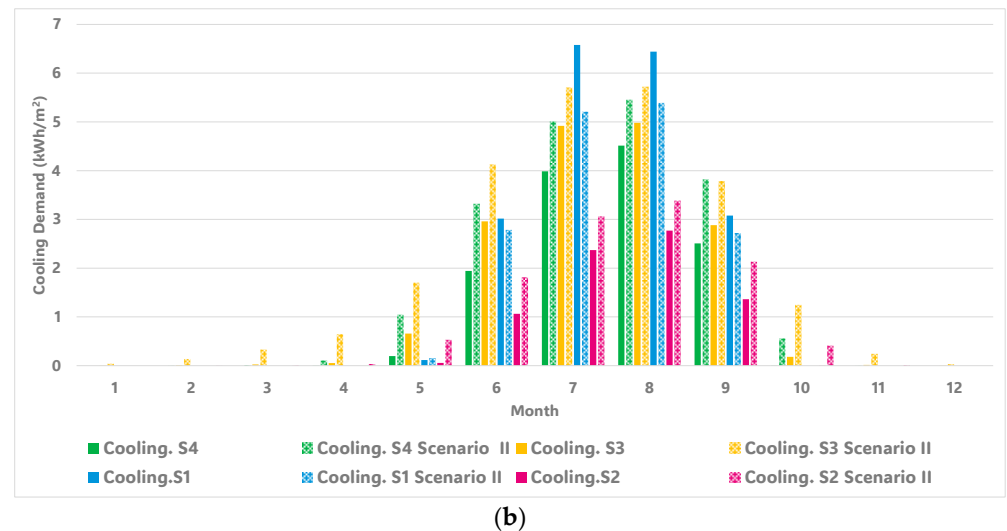


Figure 3. Monthly heating (a) and cooling (b) demand for each of the four school buildings in their current state and after implementation of the proposed improvements under Scenario II. Own elaboration.

Table 3. Evolution of heating and cooling demands across the different scenarios compared to current state.

		Current State (kWh/m ²)	Scenario II (kWh/m ²)	Increase Compared to Current State	Scenario III (kWh/m ²)	Increase Compared to Current State	Scenario IV (kWh/m ²)	Increase Compared to Current State
S1	Heating	201.56	78.81	−60.9%	86.68	−57%	112.97	−43.95%
	Cooling	19.23	16.26	−15.4%	13.19	−31.4%	14.11	−26.62%
S2	Heating	36.01	8.41	−76.6%	20.30	−43.3%	13.90	−61.3%
	Cooling	7.63	11.40	+49.4%	7.54	−1.2%	8.18	+7.20%
S3	Heating	50.23	34.73	−30.9%	39.59	−21.2%	-	-
	Cooling	16.70	23.73	+42.1%	13.43	−19.6%	-	-
S4	Heating	40.97	11.12	−72.9%	15.55	−62.04%	51.19	+24.94%
	Cooling	13.15	19.33	+47%	12.00	−8.74%	14.36	+9.2%

The trend becomes even more pronounced when analyzing hours outside the cooling setpoint, which increases significantly following the passive upgrade. These results highlight that, in the absence of active cooling systems or complementary solar protection strategies, improving the thermal envelope may exacerbate overheating issues. In relative terms, the increase is particularly notable in S2 (+64.1%) and S4 (+53.2%), while S3 and S1 also show substantial rises (+42.9% and +46.1%, respectively), reaching concerning values such as 52,377 h outside the setpoint in S4 and 49,207 h in S3. In summary, Scenario II demonstrates that, in the current climate, high-performance envelopes effectively reduce heating demand, particularly in buildings with favorable compactness and low glazing ratios (S2, S4). However, the same measures generally worsen summer comfort, especially in buildings with high WWR (S3) or where ventilation potential is reduced, making it essential to combine envelope upgrades with solar control or ventilation strategies to avoid overheating.

5.3. Scenario III: Improvement and Installation of Passive Systems on the Thermal Envelope

Scenario III evaluates the impact of specific strategies aimed at improving thermal performance under overheating conditions by reducing solar gains through glazed openings.

Two simultaneous measures are implemented: the replacement of glazing with glass featuring a solar factor $g = 0.35$, and the installation of external solar control devices adapted to the orientation of the windows. The analysis of the results shows that these solutions provide selective improvements, particularly in reducing cooling demand, although the effects vary depending on the school.

From a heating perspective, annual demands decrease compared to the current state across all buildings, though to a lesser extent than in Scenario II (see Figure 4). The reduction is more limited in S1 (from 201.56 to 86.68 kWh/m²·year; −57.0%) and in S2 (from 36.01 to 20.30; −43.6%) but remains significant in S4 (from 40.97 to 15.55 kWh/m²·year; −62.0%). The building with the smallest improvement in this aspect is S3, where heating demand drops only by 21.2%, which is consistent with its better initial condition, already featuring a mechanical ventilation system and a relatively optimized envelope. (See Table 3).

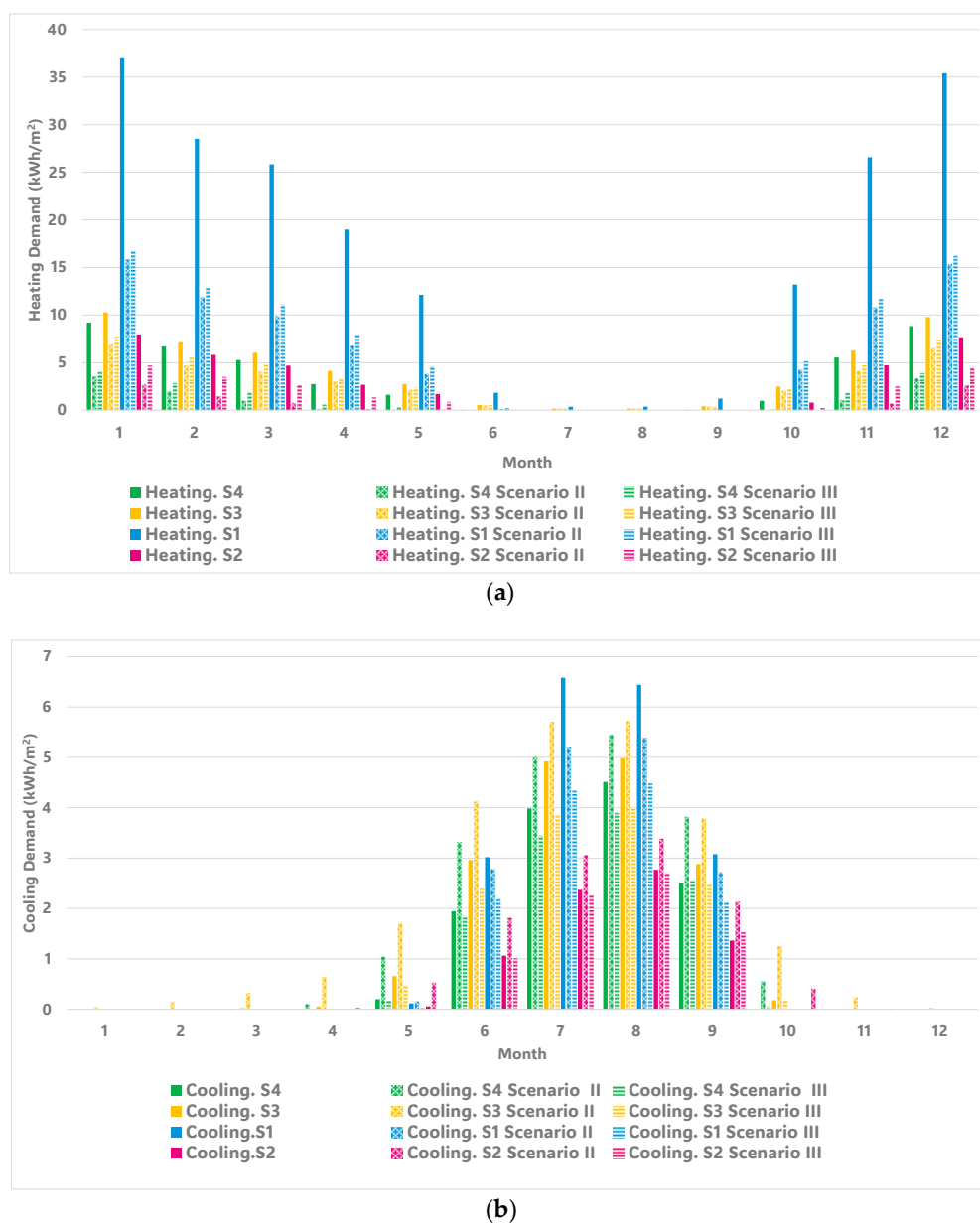


Figure 4. Monthly heating (a) and cooling (b) demand for each of the four school buildings in their current state and after implementation of the proposed improvements under Scenario III. Own elaboration.

Regarding cooling demands, the effects are more contrasted. In all four buildings, demands decrease compared to the initial state, with significant reductions in S1 (−31.0%) and S3 (−19.6%). In S2, the improvement is minimal (−1.2%), while in S4, cooling demand drops from 13.15 to 12.00 kWh/m²·year, representing a reduction of 8.7%. This correction with respect to the behavior observed in Scenario II suggests that solar control measures partially mitigate the negative impact associated with the high level of thermal insulation and the airtightness of the new windows on cooling demand.

Nevertheless, the measures applied in Scenario III do not fully reverse the increase in hours outside the cooling setpoint triggered by the previous improvements. Although there is a general improvement compared to Scenario II, the values remain significantly higher than in the initial state. In S2, hours outside the setpoint increase from 12,556 to 16,848 (+34.2%), in S4 from 34,198 to 41,394 (+21.0%), and in S1 from 8968 to 11,482 (+28.0%). Only in S3 is the increase more moderate (+10.1%), reaching 37,910 h. This highlights that while solar protections help moderate cooling loads, they are not sufficient on their own to ensure thermal comfort without active ventilation, night-time dissipation, or other adaptive strategies. (See Table 4).

Table 4. Number of hours outside the cooling set point in each scenario.

	Current State	Scenario II	Increase Compared to Current State	Scenario III	Increase Compared to Current State	Scenario IV	Increase Compared to Current State
S1	8.968	13.100	+46.1%	11.482	+28%	11.319	+26.21%
S2	12.556	20.603	+64.1%	16.848	+34.2%	10.146	−19.19%
S3	34.432	49.207	+42.9%	37.910	+10.1%	-	-
S4	34.198	52.377	+53.2%	41.394	+21.04%	40.737	+19.12%

A particularly relevant aspect is the behavior of the buildings during the school months of May, June, and September, which coincide (in the case of May and June) with the end of the academic year and student assessments. During this period, inadequate thermal conditions can directly affect comfort and cognitive performance. In S3, for example, cooling demand in May decreases from 1.70 to 0.47 kWh/m² from Scenario II to III, and in June from 4.13 to 2.40 kWh/m². In S1, there is a reduction in May (from 0.16 to 0.03) and in June (from 2.79 to 2.20). S4 also shows demand reductions in May (from 1.05 to 0.18 kWh/m²), June (from 3.32 to 1.85), and September (from 3.82 to 2.56), demonstrating effective improvement during the most critical months of the academic calendar.

Overall, Scenario III confirms that solar control strategies are effective in reducing summer cooling loads, especially in buildings with a high percentage of glazing—such as S3, where out-of-setpoint hours drop from 49,207 to 37,910—or with compromised solar exposure. These measures can partially offset the cooling penalties caused by the improvements to opaque envelopes introduced in Scenario II. However, even with these strategies, the number of cooling out-of-setpoint hours remains higher than in the initial state, with increases ranging from 10.1% in S3 to 34.2% in S2. This demonstrates that solar control alone is not sufficient to ensure thermal comfort under current climate conditions in Madrid, unless combined with ventilation or nighttime heat dissipation strategies.

5.4. Scenario IV: Improvement of the Active Systems of the Buildings

In Scenario IV, the implementation of a mechanical ventilation system with heat recovery and automatic bypass is analyzed, simulated with operation limited to school hours. The results show a heterogeneous response depending on the building. While S2

achieves a 61.3% reduction in heating demand and an improvement in thermal comfort with 19.2% fewer hours outside the cooling setpoint compared to the current state, S4 and S1 experience significant increases both in heating demand (+25% and +42.1%, respectively) and in hours outside setpoint (+19.1% and +26.3%, respectively) compared to the current state, indicating that in these cases the strategy is not effective in mitigating overheating. These results suggest that during school hours and with only the heat recovery system operating, the incoming air still exceeds comfort temperatures. Although this improves conditions compared to uncontrolled natural ventilation during the same period, it is not comparable to a continuous ventilation strategy that also includes the nighttime period.

Although the mechanical ventilation system introduced in Scenario IV does not manage to reverse the increase in cooling demand caused by the envelope improvement (Scenarios II and III), it does significantly reduce the number of hours outside the cooling setpoint compared to Scenario III, which represents a tangible improvement in hourly comfort during school hours. For example, in S2, the hours outside the setpoint drop from 16,848 h (Scenario III) to 10,146 h (Scenario IV), a 39.8% reduction; in S4, they decrease from 41,394 h to 40,737 h (−1.6%); and in S1, the improvement is smaller but still noticeable: from 11,482 h to 11,319 h (−1.4%). These reductions, although variable, show that the system helps partially mitigate the overheating caused by high airtightness and thermal insulation, especially in buildings where natural infiltration was previously the only means of heat dissipation. In conclusion, although it does not counteract the thermal load increase driven by the envelope improvement measures, it improves overall hourly performance compared to Scenario III, making it an effective measure to limit thermal discomfort.

The following summary tables are presented: on the one hand, the analysis of the evolution of heating and cooling demands across the four scenarios compared to the current state (Table 3); and on the other hand, the analysis of the evolution of hours outside the cooling setpoint in Scenario IV (introduction of mechanical ventilation with heat recovery), compared to the previous scenarios for each of the four school buildings (Table 4).

The detailed monthly heating and cooling demands for each school building under current and improved scenarios are presented in Appendix A Figures A1 and A2.

5.5. Scenarios Within the Future Climate Context

This section analyzes the energy performance and thermal comfort of the four simulated school buildings under different improvement scenarios—ranging from the current state to the inclusion of mechanical ventilation—in the projected climate context for the year 2050. Unlike the previous analyses focused on current climatic conditions, this section assesses the future effectiveness of proposed measures under sustained temperature increases, particularly during spring and autumn months when the schools are in use. The results reveal significant differences in the performance of each strategy depending on the building type, allowing the identification of both robust strategies against climate change and those that may lose effectiveness or even exacerbate thermal discomfort if not appropriately implemented. The projected monthly heating and cooling demands of the buildings in the 2050 climate scenario are summarized in Appendix A Figure A3.

In School S4, the projected evolution to 2050 shows a sharp decrease in heating demand in the baseline scenario (−43.4%), accompanied by a significant increase in cooling demand (+83.9%). Within this new context, the improvement strategies adopted in the various scenarios show contrasting behaviors. Scenario II, focused on envelope enhancement, effectively reduces heating demand (−79.6%) but at the cost of a substantial rise in cooling (+26.8%) and the highest number of hours outside the comfort range among all scenarios (68,735 h; +48.0%). In contrast, Scenario III, which adds solar protections and solar-control glazing, significantly reduces cooling load (−16.2% compared to Current state 2050), as

well as hours outside the comfort range (58,197 h; -12.5%). Scenario IV, incorporating mechanical ventilation with heat recovery and bypass, emerges as the most balanced strategy. While it does not reach the lowest heating ($32.46 \text{ kWh/m}^2\cdot\text{year}$) or cooling ($25.30 \text{ kWh/m}^2\cdot\text{year}$) demands, it does reduce hours outside the comfort range to 57,339 h (-23.5% compared to Scenario II and -1.8% vs. Scenario III), partially offsetting the negative effects of over-insulation and airtightness. Overall, the results indicate that by 2050, passive solar control and ventilation strategies will play a decisive role in maintaining thermal comfort, whereas envelope improvements alone will be insufficient in increasingly warm climates.

In School S2, 2050 projections reveal a notable shift in the energy needs of teaching spaces. The envelope improvement scenario (Scenario II), based on applying ETICS and airtight windows, reduces heating demand by 82.7% compared to the current state in 2050, but significantly increases cooling demand ($+23.2\%$) and the number of hours outside the cooling setpoint ($+51.1\%$). This situation is exacerbated in Scenario III (solar protections and glazing), where heating demand remains lower than the current state (-69.4%), but cooling increases by 11.3% and hours outside the setpoint by 20.8% , indicating that passive measures fail to compensate for the thermal discomfort associated with envelope airtightness. The incorporation of a mechanical ventilation system with heat recovery (Scenario IV) substantially improves this behavior. While the heating demand reduction is slightly lower (-67.4% vs. current state), the cooling increase is more contained ($+8.3\%$). Most notably, thermal comfort improves significantly: hours outside the setpoint decrease by 19.5% compared to the current state and by 21% versus Scenario III, making it the most effective strategy for limiting future overheating in this building.

In School S1, simulations for 2050 show that all analyzed measures (Scenarios II, III, and IV) significantly reduce heating demand compared to the projected current state (Current state 2050), with the envelope improvement strategy (ETICS and windows, Scenario II) being the most effective (-64.1%). This scenario also achieves the greatest reduction in hours outside the cooling setpoint (-23.5%), suggesting a positive impact on both energy efficiency and thermal comfort. Scenario III (solar protections and glazing) yields more moderate improvements, with a 59.8% reduction in heating and 8.5% in setpoint hours, while Scenario IV (mechanical ventilation with heat recovery) proves the least effective in terms of thermal demand, with a 45.1% reduction in heating and only 5.7% in hours outside the cooling setpoint. Unlike other buildings, where mechanical ventilation emerges as an effective solution against overheating, its impact in S1 is limited, likely due to the building's smaller glazed area and high initial permeability, making forced ventilation less critical.

In School S3, which already includes mechanical ventilation in the baseline scenario, the 2050 results show that the proposed improvement measures fail to reverse the negative impact of climate change on cooling demand and thermal comfort. Cooling demand increases significantly in all scenarios compared to the current state, reaching a rise of 29.3% in Scenario II and 24.3% in Scenario III. Similarly, cooling out-of-setpoint hours increase significantly, especially in Scenario II ($+36.8\%$ compared to the current state). Although Scenario III slightly reduces these out-of-setpoint hours ($+6.6\%$ compared to the current state), the result is still worse than the initial condition.

Overall, the results demonstrate that while envelope improvements are essential for reducing heating demand, they must be accompanied by active ventilation strategies to avoid counterproductive effects on thermal comfort during warm periods. Controlled ventilation helps mitigate the negative side effects of airtightness and significantly improves hourly comfort—a crucial factor in the climate change scenario of 2050. In most cases, mechanical ventilation with heat recovery enhances comfort relative to Scenario

III, although it does not fully reverse the overheating caused by envelope upgrades. This improvement is especially notable in School S2, whereas in other buildings, the effects are more limited or even adverse. In the 2050 horizon, characterized by a substantial increase in outdoor temperatures, the impact of these strategies is amplified, highlighting that universal solutions are not equally effective across all buildings and climates. The wide variability in the results underscores the need for climate- and building-specific adaptation strategies, taking into account morphology, orientation, construction system, and usage patterns. In the context of climate change, the design of passive ventilation and conditioning solutions must be carefully tailored to the specific conditions of each school in order to ensure their effectiveness and long-term sustainability. Table 5 summarizes the evolution of heating and cooling demands across the different retrofit scenarios for 2050, while Table 6 presents the corresponding hours outside the cooling setpoint.

Table 5. Evolution of heating and cooling demands across the different scenarios compared to the current state (2050).

		Current State (kWh/m ²)	Scenario II (kWh/m ²)	Increase Compared to Current State	Scenario III (kWh/m ²)	Increase Compared to Current State	Scenario IV (kWh/m ²)	Increase Compared to Current State
S1	Heating	133.86	48.03	−64.1%	53.83	−59.8%	73.55	−45.1%
	Cooling	38.12	28.97	−24%	24.71	−35.2%	26.14	−31.4%
S2	Heating	20.29	3.5	−82.7%	6.2	−69.44%	6.61	−67.4%
	Cooling	16.75	20.63	+23.16%	15.33	−8.47%	15.27	+8.83%
S3	Heating	32.09	23.5	−26.77%	26.23	−18.26%	-	-
	Cooling	27.04	35.01	+29.47%	21.21	−21.56%	-	-
S4	Heating	23.18	4.73	−79.6%	7.59	−67.3%	32.46	+40%
	Cooling	24.2	30.68	+26.8%	20.28	−16.12%	25.3	+4.5%

Table 6. Number of hours outside the cooling set point in each scenario (2050).

	Current State	Scenario II	Increase Compared to Current State	Scenario III	Increase Compared to Current State	Scenario IV	Increase Compared to Current State
S1	15.784	18.486	+17.1%	17.183	+8.9%	16.880	+6.9%
S2	19.672	29.725	+51.10%	23.773	+20.84%	23.506	−19.48%
S3	45.886	62.687	+36.67%	49.073	+6.99%	-	-
S4	46.442	68.734	+48%	58.197	+25.3%	57.339	+23.5%

The monthly heating and cooling demands of the four school buildings, both in their current state and under the projected 2050 climate scenario with the proposed retrofit measures, are shown in Appendix A Figures A4 and A5.

6. Discussion

6.1. Current Situation and Possible Improvements

The comparative analysis of energy demands in the current state (prior to the rehabilitation scenarios) highlights the influence of building morphology and envelope configuration on the thermal performance of buildings. In the analyzed case studies, heating demands range from 36.01 kWh/m²·year for S2 to 201.56 kWh/m²·year for S1. These values span a wide range that overlaps with those found in other school buildings analyzed in previous studies in Europe and the Middle East, with figures ranging from 11.1 kWh/m²·year [21] or

11.4 kWh/m²·year [12] in studies conducted in warmer climates (Andalusia and Jordan), to 75.9 kWh/m²·year [30] or even 152–188 kWh/m²·year [13]. This range difference highlights the strong heterogeneity in the school building sector, with extreme values reflecting the influence of previous interventions, the year of construction, or the specific climate of each building. Therefore, although different studies have identified significant variability in the energy performance of school buildings, local cases generally present a wider dispersion, with a higher minimum value and a maximum above the upper range reported in similar studies. It should also be noted that the value for S1 (201.56 kWh/m²·year) is by far the highest among the four schools studied, due to its specific circumstances, whereas the remaining heating demand values (50.23, 40.97, and 36.01 kWh/m²·year) align more closely with the average results found in the literature. Regarding the influence of the various improvement measures proposed and analyzed in different studies compared with the results obtained in the present research, reductions achieved through the incorporation of ETICS and improved window systems range from 48% to 56% [13], slightly below the improvement percentages obtained in this study (30.91% in S3 to 76.6% in S2). When the proposed improvements also include solar protection—equivalent to Scenario III in this study—the range of heating demand reductions reported in other studies decreases to 17.7% [21], 36.4% [12], and up to 56% [17], values in line with the reductions achieved in this study, which are slightly lower for a comparable scenario (21.2% in S3 to 62.04% in S4). Finally, the incorporation of mechanical ventilation alongside these energy efficiency measures—equivalent to Scenario IV in this study—proves to be the most variable in terms of heating demand variation. In the present study, the range goes from a 61.3% reduction in S2 to a 24.94% increase in S4 compared to the baseline scenario. Other studies with similar measures report a heating demand reduction of 32% [43] when incorporating mechanical ventilation with heat recovery.

With respect to cooling demand, in the current state, the four locally analyzed school buildings present values between 7.63 and 19.23 kWh/m²·year, with S1 (19.23 kWh/m²·year) and S3 (16.70 kWh/m²·year) recording the highest figures. Despite the relevance of this indicator, especially in the current climate change context, few studies address cooling demand, as this has not historically been a major issue in many countries, particularly in Northern and Central Europe. This is reflected, for instance, in the ENERGE project, which does not collect specific data on the subject. However, when compared with other research on school buildings, the present results are lower than those observed in schools in the Middle East—34.4 kWh/m²·year [12] or even 77.1 kWh/m²·year [30]—and are very much in line with studies carried out in southern Spain—19.6 kWh/m²·year [21]. Regarding the influence of the analyzed improvement scenarios, some envelope measures (increased insulation) can raise cooling demand, making it essential to address glazing and solar control interventions [44], as observed in this study's results. Envelope improvements can lead to increases in cooling demand, a circumstance already highlighted by other authors who identified up to a 30% increase [11]. In line with this, the results obtained in this study for envelope improvements—adding façade insulation and replacing windows with higher-performance models (Scenario II)—show that in three of the four schools, cooling demand rises between 42.1% in S3 and 49.4% in S2. However, when measures specifically aimed at mitigating cooling demand are included—such as solar protection or solar-control glazing, equivalent to Scenario III in this study—recent studies report reductions in cooling demand ranging from 15.9% [21] to 59.2% [12]. In the present case, these cooling demand reductions with solar control measures are somewhat more modest: 1.2%, 8.74%, 19.6%, and 31.4% for S2, S4, S3, and S1, respectively. This outcome is also influenced by each school's baseline conditions and the cumulative measures applied in Scenario I, which increased cooling demand compared to the original state, as previously noted. Regarding

ventilation [45], point out issues associated with outdoor air quality, which, although not addressed in the present study, could be affected by the presence of mechanical ventilation with heat recovery (MVHR).

As for cooling setpoint exceedance hours associated with overheating, the school analyses in this study show considerable variability, ranging from 8968 h/year in S1 to 34,432 h/year in S3. Buildings that are taller and have large, glazed areas, low airtightness, and a high form factor are more vulnerable to overheating [46]. This aligns with the present results: S3 and S4 record the highest setpoint exceedance hours in the baseline scenario (34,432 and 34,198 h/year respectively). Both have the largest glazed areas among the schools studied; moreover, S3 has one of the highest form factors and S4 the highest. Implementation of envelope improvements, contrary to expectations, increases the number of cooling setpoint exceedance hours. This effect is particularly pronounced in schools without mechanical ventilation, such as S4, where setpoint exceedance hours rise by 19.12% (from 34,198 to 40,737 h/year), and in S1, where they rise by 26.21% (from 8968 to 11,482 h/year). In the case of S1, this behavior may be due to its original state (Scenario I), where the thermal envelope had high air permeability, allowing for heat dissipation during peak load periods; however, the improvements have increased airtightness, reducing this dissipation capacity. Only S2 reduces setpoint exceedance hours, with all improvements implemented, by 19.19%, in line with other studies that estimate reductions in discomfort hours of around 18–32% [24] or 23% [43] for similar scenarios. The findings of this study suggest that, in the absence of active ventilation systems and/or solar control elements, improving the building envelope may worsen thermal performance in summer.

It should be noted that although envelope retrofitting significantly reduces heating demand, it also leads to an increase in cooling needs [47]. Although it is contrary to some research, other studies have highlighted the importance of controlling radiative heat transfer [48]. This effect is mainly related to the improvement in airtightness and insulation, which reduces natural infiltration and heat dissipation during summer periods. As a result, internal gains accumulate more easily, making buildings more prone to overheating if additional measures are not considered.

The results highlight the importance of considering the trade-offs between energy efficiency and thermal comfort. While improvements in the thermal envelopes of buildings provide substantial reductions in heating demand, they may simultaneously increase the risk of overheating. These findings emphasize that retrofit strategies should not focus solely on building envelope improvements, but should be combined with shading devices, controlled natural or mechanical ventilation, and adaptive comfort approaches. Such integrated packages are essential to ensure that energy savings do not compromise indoor comfort, especially under future climate conditions.

6.2. Future Situation and Possible Improvements

In the context of climate change, the year of construction is one of the key parameters due to its relationship with construction systems [44]. Likewise, in various studies conducted under climate change conditions, the conclusions are similar regarding the reduction in heating demand, reaching 24% [28] or even 28% [46]. In this study, the percentage reductions in heating demand under the climate change scenario—which involves a general increase in outdoor temperatures—are somewhat more pronounced, ranging from −33.59% in S1 to −43.66% in S4.

At the same time, and in line with other research, improving the thermal envelope in warm climates—without including solar control elements—leads to an increase in cooling demand that can reach ~80–91% under future climate conditions, especially when insulation is combined in a non-optimal way or without complementary measures such as solar control

or glazing improvements [11]. In our case, this increase in cooling demand compared to the current state ranges from 61.86% in S3 to 119.55%, which is slightly lower than the 166% identified by Akkose, Gizem et al. [28]. In this regard, different studies model the performance of school buildings equipped with air conditioning, showing increases of up to 13 kWh/m² by 2050 when the setpoint is maintained at 21 °C in schools in southern England that only have thermal insulation [31]. This highlights the importance of incorporating other combined strategies and adopting urgent measures to control the situation in order to prevent deterioration in thermal comfort, health, and academic performance in school environments [49].

With regard to ventilation (Scenario IV), its inclusion will be essential to mitigate thermal discomfort in summer, especially when insulation hinders the dissipation of internal loads [46]. Nevertheless, in the present study, mechanical ventilation with heat recovery shows virtually no additional benefit compared to the other measures. It is important to emphasize once again that nighttime ventilation was not included in the simulation, which significantly limits the potential effectiveness of this strategy. Although it does manage to reduce the number of hours within the comfort range by 19.48% in S2 compared to the original state, and in S4 and S1, it does reduce the hours outside the set-point range compared to Scenario III, it does not do so compared to the baseline state. In addition, it increases cooling demand by +8.83% in S2 and +4.5% in S4. Only in the case of S1 is there a significant reduction in cooling demand (−31.4%). In this respect, different hypotheses are proposed to improve energy efficiency with ventilation systems:

- Modification of the daytime operating schedule of the ventilation system: Mechanical ventilation was studied operating during school hours (08:00–17:00). This schedule, coinciding with high external thermal loads, may favor the intake of warmer outdoor air during the hottest months. Under summer conditions, it would be advisable to adjust the operation to nighttime hours and early mornings, taking advantage of more favorable outdoor conditions.
- Reduction of airtightness: Although airtightness reduces thermal losses in winter, it also limits spontaneous natural ventilation in summer, which can lead to greater heat accumulation if mechanical ventilation is insufficient or not dynamically adjusted. It would be of interest to develop passive natural ventilation systems that complement the mechanical systems described above, which operate strictly according to regulatory standards. These systems would be integrated into the building envelope (both opaque elements and openings) and activated during summer periods when outdoor conditions are more favorable than indoor ones. Their operation could be enhanced by taking advantage of phenomena such as cross-ventilation through façades and by characterizing those façades based on whether they are windward or leeward, according to the prevailing winds during warm periods.

In the 2050 scenario, mechanical ventilation with heat recovery (Scenario IV) provides limited additional benefits compared to the current climate. This is mainly because the system was simulated as operating only during school hours, so nighttime free cooling was not applied in the simulations. In addition, outdoor air temperatures are expected to remain higher for longer periods, which would further reduce the potential of ventilation to provide relief during daytime operation. From this point of view, however, although it was not simulated in this study, the incorporation of controlled nighttime ventilation strategies is expected to significantly improve comfort conditions and help mitigate overheating under future climate scenarios, in line with other research [50,51]. It should also be emphasized that ventilation should not be regarded solely as a thermal control strategy, but as a matter of indoor health and air quality, as highlighted by different research. Indeed, as shown in the results, improving the airtightness of the thermal envelope substantially reduces

natural ventilation rates, potentially compromising indoor environmental quality. Then, in school buildings characterized by high occupancy density and a particularly vulnerable population, the incorporation of energy-efficient ventilation systems must be considered a priority. Under climate change conditions, this becomes even more critical, requiring solutions that ensure adequate indoor air quality while minimizing their impact on energy demand and consumption.

As for hours outside the setpoint range, there is an increase in the number of hours above 26 °C, which implies an improvement in winter conditions but an increase in summer discomfort hours of +33.31% in S3, +35.83% in S4, +56.66% in S2, and +76.01% in S1 compared to the 2025 baseline scenario. The most affected areas are the most massive and south-facing ones [52]. This situation has already been identified by various authors as a consequence of rising temperatures, although without quantitative data evaluation [45]. However, based on this study, it is confirmed that passive adaptation of buildings will not be sufficient to address future thermal stress, making it essential to introduce active or hybrid solutions that simultaneously address cooling and controlled ventilation.

In light of the results, it is essential to find a balance between thermal insulation and the building's capacity to dissipate heat, with ventilation and shading being two key parameters [46]. Furthermore, each case must be studied individually, since the differences detected among the schools are attributable to their urban setting, morphology, orientation, construction configuration, and usage conditions. Moreover, under climate change conditions, it is clear that the use of passive measures alone may not be sufficient [44].

6.3. Discussion in Response to the Research Questions

This section discusses the main findings of the study in direct relation to the research questions defined in Chapter 3. The results are examined not only in terms of energy performance and thermal comfort under current and future climate conditions, but also with respect to the effectiveness of retrofit strategies and their policy implications. The aim is to provide a comprehensive answer to each research question, ensuring consistency between the objectives, results, and conclusions of the study.

6.3.1. Current Performance of School Buildings Under Present Climate Conditions (RQ1)

How do school buildings in Madrid—characterized by high internal loads, limited HVAC systems, and a vulnerable user population—perform in terms of energy demand and thermal comfort under current climate conditions?

The current state analysis shows that the four schools present very heterogeneous behavior in terms of energy demand and thermal comfort, largely as a consequence of their construction period, envelope characteristics, and ventilation practices. Schools built before the implementation of modern regulations (S1, S2) display higher heating demands and poorer envelope performance, while the more recent ones (S3, S4) show lower heating needs but already exhibit a stronger tendency towards overheating during warm periods. A common feature across all cases is the absence of active cooling systems, in contrast to the widespread presence of heating systems designed exclusively for winter conditions. This circumstance, combined with the high internal loads derived from dense occupancy and continuous equipment use, makes schools especially vulnerable to discomfort during warm periods. Furthermore, the presence of a vulnerable user population—children with less efficient thermoregulation mechanisms—intensifies the health risks associated with overheating. These findings suggest that school buildings do not fully align with standard retrofit approaches, mainly those conceived of as residential buildings. On the contrary, their specific characteristics require tailored renovation strategies that explicitly address the limitations of HVAC systems, high internal loads, and sensitivity to overheating. This

reinforces the need for differentiated guidelines for school buildings instead of directly applying generic retrofit criteria.

6.3.2. Impact of Envelope Retrofitting and Loss of Uncontrolled Ventilation (RQ2)

How does envelope retrofitting—especially interventions on windows—affect the removal of uncontrolled ventilation typical of the original construction context, and what scope should such measures have in schools?

Interventions in the building envelope, particularly on windows, constitute one of the most common strategies in energy retrofitting. However, the results show that these actions, when applied following standardized criteria, can have unintended consequences in the case of schools. The replacement of windows and the improvement of airtightness reduce the uncontrolled ventilation that was present in the original construction context, which, while helping to decrease thermal losses in winter, also limits heat dissipation in summer. This effect is especially relevant in buildings without active cooling systems, where uncontrolled natural ventilation is often the only means of relief against overheating. In this study, it is observed that after the application of envelope improvements, heating demand decreases significantly, but cooling demand increases notably, especially under future climate conditions. This highlights that the application of standardized retrofit criteria is neither sufficient nor appropriate for this type of building. Consequently, the scope of envelope interventions in schools should be reconsidered, incorporating complementary strategies—such as shading devices, mechanical ventilation with heat recovery, or adaptive comfort measures—that allow balancing energy savings with protection against overheating. Only in this way can envelope improvements deliver net benefits in terms of efficiency and comfort in the school context.

6.3.3. Future Climate Conditions and Projected Building Performance for 2050 (RQ3)

How will the energy and comfort performance indicators of the analyzed schools evolve under projected climate change scenarios for 2050?

The evaluation of schools under the climate conditions projected for 2050 confirms a significant deterioration in their energy performance and comfort conditions. In all cases, cooling demand and hours outside the comfort range increase, while heating demand progressively decreases. This shift in the energy balance highlights that, in the future, the main challenge for school buildings will not be reducing winter heat losses, but managing summer overheating. The results show that buildings constructed in more recent periods, with higher levels of insulation and airtightness, experience the sharpest increase in cooling demand, reflecting the vulnerability of modern school typologies to climate change. In contrast, older schools with more permeable envelopes, although still showing high heating demand, display relatively less unfavorable behavior in response to rising outdoor temperatures. Another relevant aspect is that the warm period, previously concentrated in the summer months and with little impact on the school calendar, is now expanding significantly. High temperatures now begin earlier and extend into early autumn, which means that overheating directly affects the school term and, consequently, learning conditions and student performance. Overall, the analysis projected for 2050 highlights that adapting schools to climate change will require prioritizing strategies that specifically address the risk of overheating, ensuring the protection of an especially vulnerable user population.

6.3.4. Effectiveness of Retrofit Strategies: Envelope, Passive Systems, and Active Systems (RQ4)

What is the relative effectiveness of different retrofit strategies in reducing energy demand and mitigating discomfort?

The comparison of the different retrofit scenarios makes it possible to identify the strengths and limitations in each of the strategies analyzed. The improvement of the thermal envelope through ETICS systems and high-performance glazing achieves the greatest reductions in heating demand, with savings exceeding 40–50% in some cases. However, this strategy increases cooling demand, especially in newer and more airtight buildings, confirming the need to accompany it with other measures that mitigate overheating. Passive solar control strategies, such as the incorporation of external shading, are more effective in reducing discomfort hours associated with overheating, significantly limiting the increase in cooling demand under climate change scenarios. Finally, the incorporation of mechanical ventilation with heat recovery emerges as the most balanced strategy, providing reductions in heating demand while at the same time improving thermal comfort thanks to controlled and stable ventilation. Although its impact on reducing cooling demand is more moderate than that of solar protection, this measure clearly improves indoor environmental quality and the resilience of school buildings to future climates. It should also be noted that, although not addressed in this study, the effectiveness of the ventilation system could be considerably enhanced if its operation were extended to the nighttime period (free cooling technique), instead of being limited exclusively to school hours as simulated here.

6.3.5. Trade-Offs Between Energy Efficiency and Thermal Comfort (RQ5)

What trade-offs emerge between energy efficiency and thermal comfort when applying these retrofit strategies, and how can they inform balanced renovation policies for schools?

The comparative analysis of the scenarios confirms the existence of significant trade-offs between energy efficiency and thermal comfort in the schools analyzed. While envelope improvements result in substantial reductions in heating demand, they significantly increase the risk of overheating and cooling demand. This paradox highlights that strategies primarily conceived for cold climates or residential typologies can have counterproductive effects in school buildings without active cooling systems. In the specific context of Madrid, characterized by cold winters and hot summers, these tensions between energy savings and indoor comfort are particularly evident. While in predominantly cold climates the reduction of heating demand may take priority, in warmer or Mediterranean climates, the risk of overheating becomes central and cannot be ignored, especially in the context of climate change. Solar control measures and mechanical ventilation with heat recovery partly mitigate this imbalance, but they are not free of limitations: solar protections reduce summer discomfort hours but, logically, do not improve winter performance; mechanical ventilation enhances comfort and air quality but requires additional electricity consumption and careful management of operating schedules to realize its full potential. These results reinforce the idea that there is no single optimal solution but rather the need for customized strategies that balance energy savings and indoor comfort. They also underline the importance of ensuring that renovation policies not only prioritize energy efficiency measured in terms of demand (and therefore consumption) reduction, but also integrate indicators of user comfort and health, particularly in the case of schools.

6.3.6. Policy Implications and Alignment with European Renovation Goals (RQ6)

How can the results of this study inform decision-making in renovation policies and regulatory adaptation towards nearly zero-energy and zero-emission school buildings in the European framework?

The results of this study provide relevant evidence for the definition of renovation policies and regulatory adaptation in the European framework towards nearly zero-energy and zero-emission buildings. The analysis of schools in Madrid shows that the simple application of standardized criteria does not guarantee a balanced improvement in terms

of energy efficiency and comfort, especially in the face of the overheating challenge. This finding highlights the need for renovation policies to consider not only indicators of energy demand reduction but also metrics of comfort and health, which are essential in educational environments with highly vulnerable users. Very often, energy efficiency improvement is simplistically equated with increased thermal insulation of the envelope. While this approach may be valid in central and northern European countries, where winter conditions dominate most of the year, it is insufficient in southern or warmer climates. Madrid lies precisely at the intersection between the cold northern climates and the warm southern ones, which makes both the reduction of winter heat losses and the prevention of summer overheating equally relevant objectives. In addition, the evaluation under future climate scenarios reinforces the urgency of incorporating climate change adaptation into renovation strategies. The extension of the warm period and the increase in hours outside the cooling setpoint range confirm that interventions cannot be limited to winter efficiency objectives, but must also include overheating mitigation measures. In this way, the findings of the study can serve as a basis for guiding school renovation programs within national and European policies, promoting integrated approaches that combine energy savings, climate resilience, and occupant well-being. This is consistent with the European Union's goals of transforming the building stock into nearly zero-energy and subsequently zero-emission buildings by 2050.

7. Conclusions

When comparing the effectiveness of improvement measures under current climatic conditions and the projected 2050 scenario, a clear shift in their performance can be observed. Under present-day conditions, envelope improvements (Scenario II) consistently achieve the greatest reductions in heating demand—typically above 60% and even reaching 76.6% in cases such as S2—although they tend to increase cooling demand (by between +20% and +50%) and out-of-setpoint hours due to high airtightness and insulation levels. Solar control strategies (Scenario III) partially offset this penalty, with cooling demand reductions of up to −31% (S1) compared to the baseline scenario, while the incorporation of mechanical ventilation (Scenario IV) can further improve thermal comfort, reducing out-of-setpoint hours by more than 35% in some cases compared to Scenario III. However, in the 2050 climatic context, the relative advantage of envelope-only upgrades decreases: although heating demand reductions remain very high—above 60% in most cases, the penalty in cooling demand and out-of-setpoint hours increase considerably, with rises that can exceed +80% in cooling demand (S4) and +40% in out-of-setpoint hours (S2). In this future scenario, passive solar control measures and controlled ventilation become essential tools for mitigating overheating, whereas relying solely on enhanced insulation can lead to a significant deterioration in thermal comfort. This evolution highlights the need to shift from an energy efficiency strategy focused mainly on winter performance to a balanced year-round comfort approach, which, in climates such as Madrid—with cold winters and very hot summers—must place particular emphasis on cooling in the emerging climate context toward which we are heading.

In conclusion, the results obtained in the study show that without specific action on the building envelope and systems, the impact of climate change will lead to a widespread increase in cooling demand and in hours outside the setpoint range. Passive measures focused on improving the envelope are key to mitigating this effect, although they must be complemented by active strategies for controlled ventilation and solar control in order to ensure thermal comfort in future climate scenarios.

A general shift in strategy is therefore necessary regarding the improvement of energy efficiency in school buildings. Efforts should focus on enhancing the passive performance

of these buildings with a more integrated and seasonal perspective. Indeed, so-called “energy retrofits” that focus almost exclusively on reinforcing the insulation of the building envelope significantly reduce its original air permeability, especially in older buildings. In such cases—like those analyzed in this study—it is also essential to ensure ventilation conditions that restore an adequate level of air renewal and help mitigate the negative impact that these “conventional” interventions have on thermal comfort during warm periods, which are significantly worsened in the context of climate change and rising outdoor temperatures.

One of the essential conclusions of this study is that no retrofit strategy affecting the airtightness of the envelopes in school buildings should be undertaken without simultaneously reviewing ventilation conditions in order to ensure the minimum airflow rates required to maintain hygienic and healthy indoor air quality.

Another key takeaway from this study is that the retrofit priority for school buildings in Madrid must strike a balance between reducing heating demand and mitigating overheating, which will become the dominant challenge in future climate scenarios. This requires moving beyond insulation-only approaches and adopting integrated renovation packages that combine thermal envelope improvements with effective solar control and, most importantly, energy-efficient ventilation systems that guarantee the necessary airflow and air renewal rates under all circumstances. Such an approach is essential not only to ensure energy efficiency, but also to safeguard thermal comfort and indoor air quality in buildings with high occupancy density and a particularly vulnerable population.

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Data Availability Statement: The data supporting the findings of this study were generated through building energy simulations using TeKton3D and CCWeatherGen. These are simulation results, not measured datasets. All relevant aggregated results are presented within the article. Due to confidentiality reasons related to the school buildings analyzed, the complete simulation models are not publicly available.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Data Tables Obtained from Building Energy Simulations

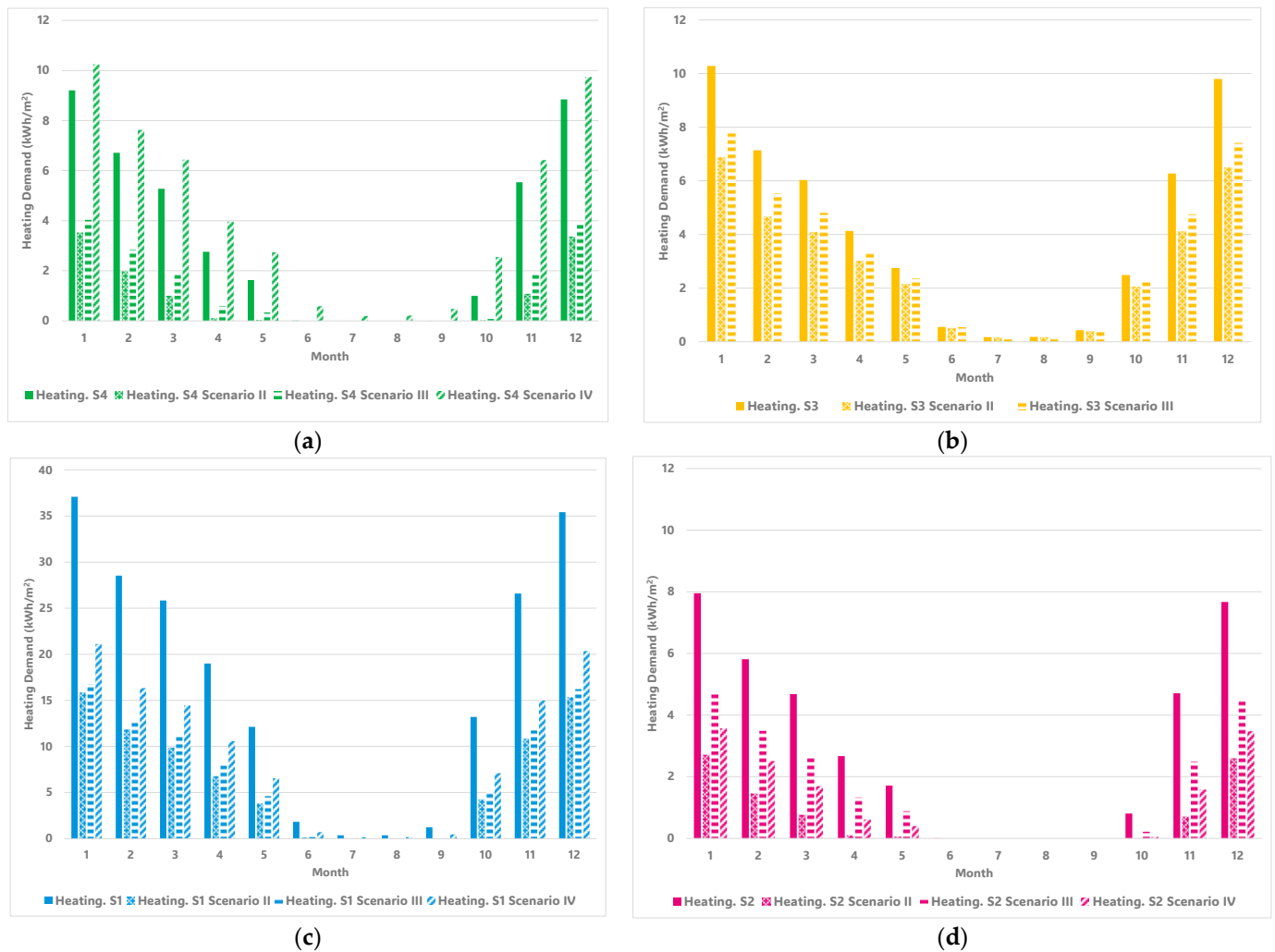


Figure A1. Monthly heating demands for each of the four school buildings, S4 (a), S3 (b), S1 (c), and S2 (d), in their current state and with the implementation of the proposed improvements in Scenarios II, III, and IV. Own elaboration.

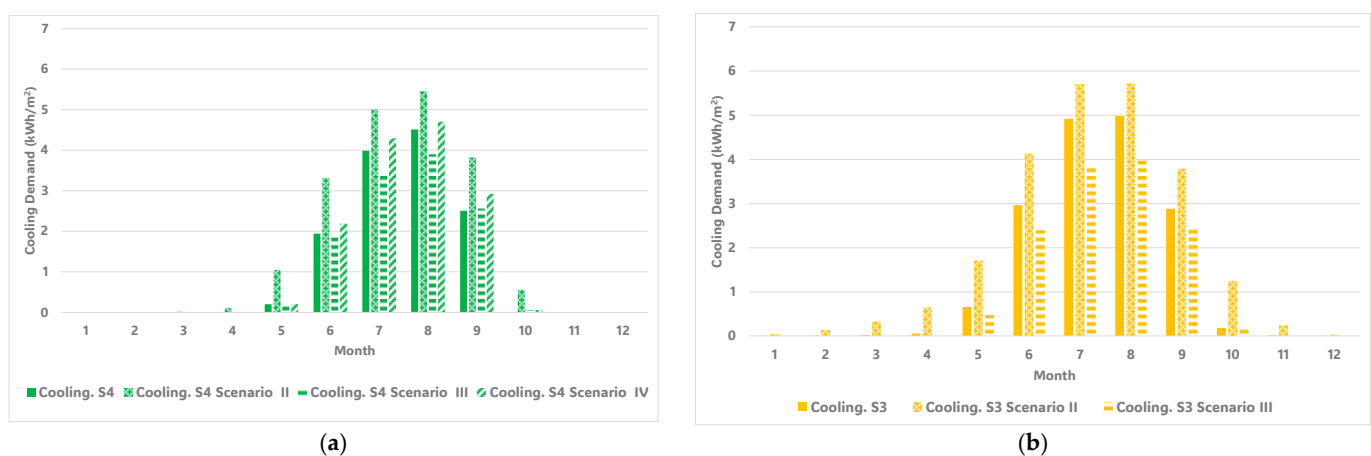
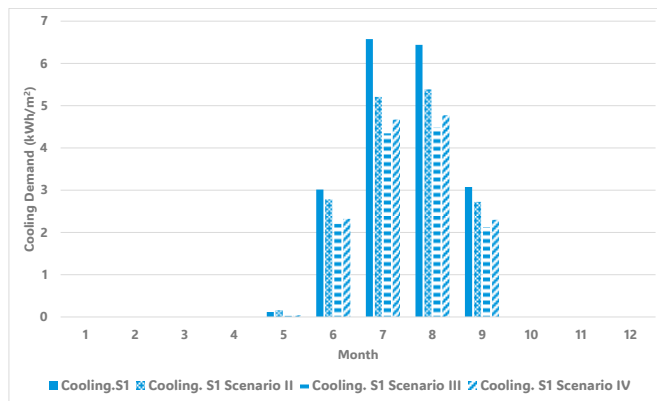
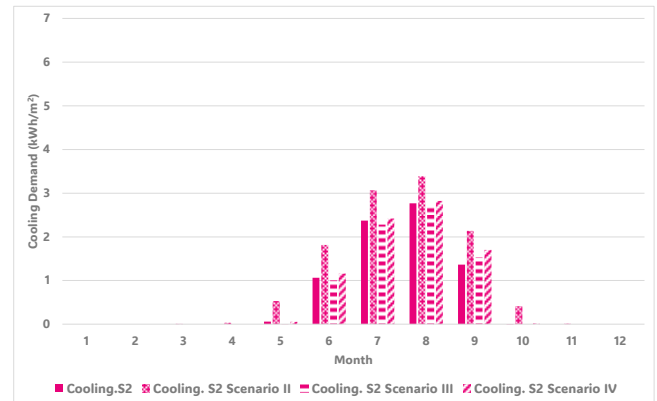


Figure A2. Cont.

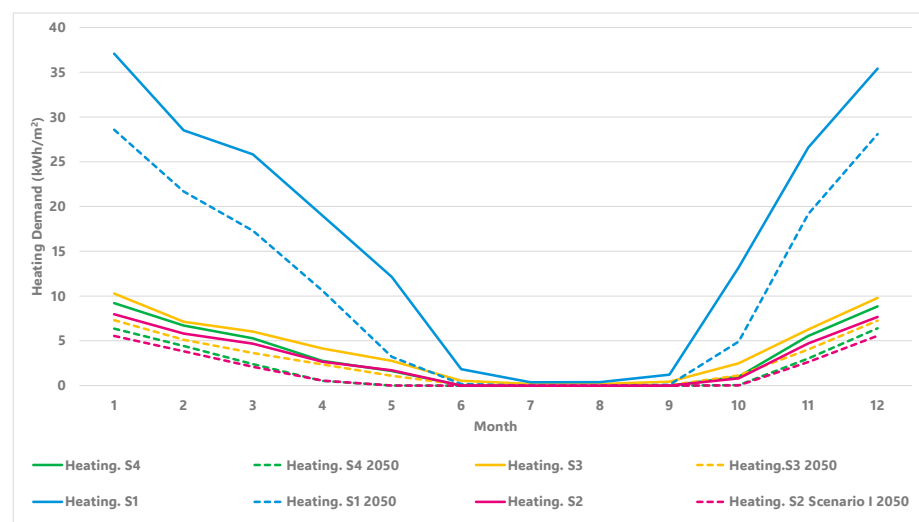


(c)

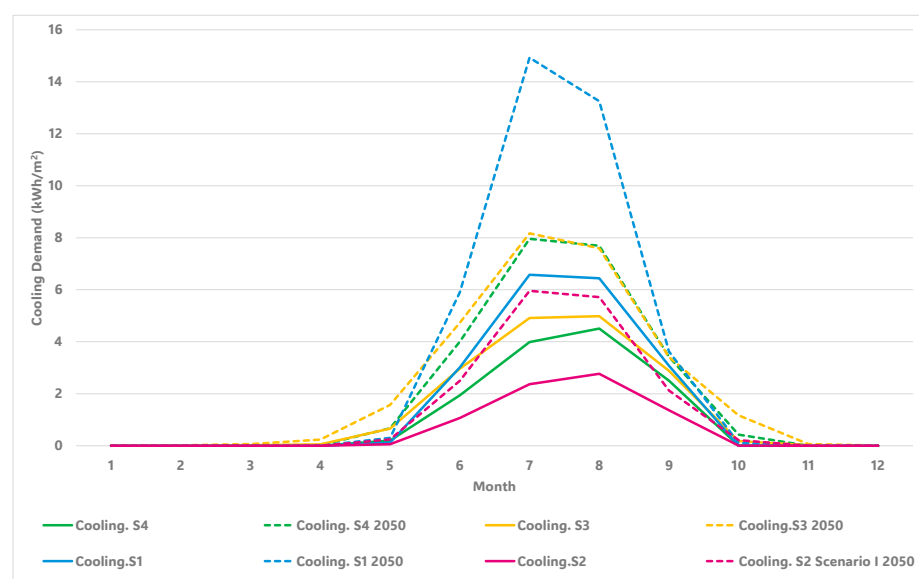


(d)

Figure A2. Monthly cooling demands for each of the four school buildings, S4 (a), S3 (b), S1 (c), and S2 (d), in their current state and with the implementation of the proposed improvements in Scenarios II, III, and IV. Own elaboration.



(a)



(b)

Figure A3. Monthly heating (a) and cooling (b) energy demands of the four school buildings in their current state and in the 2050 climate scenario. Own elaboration.

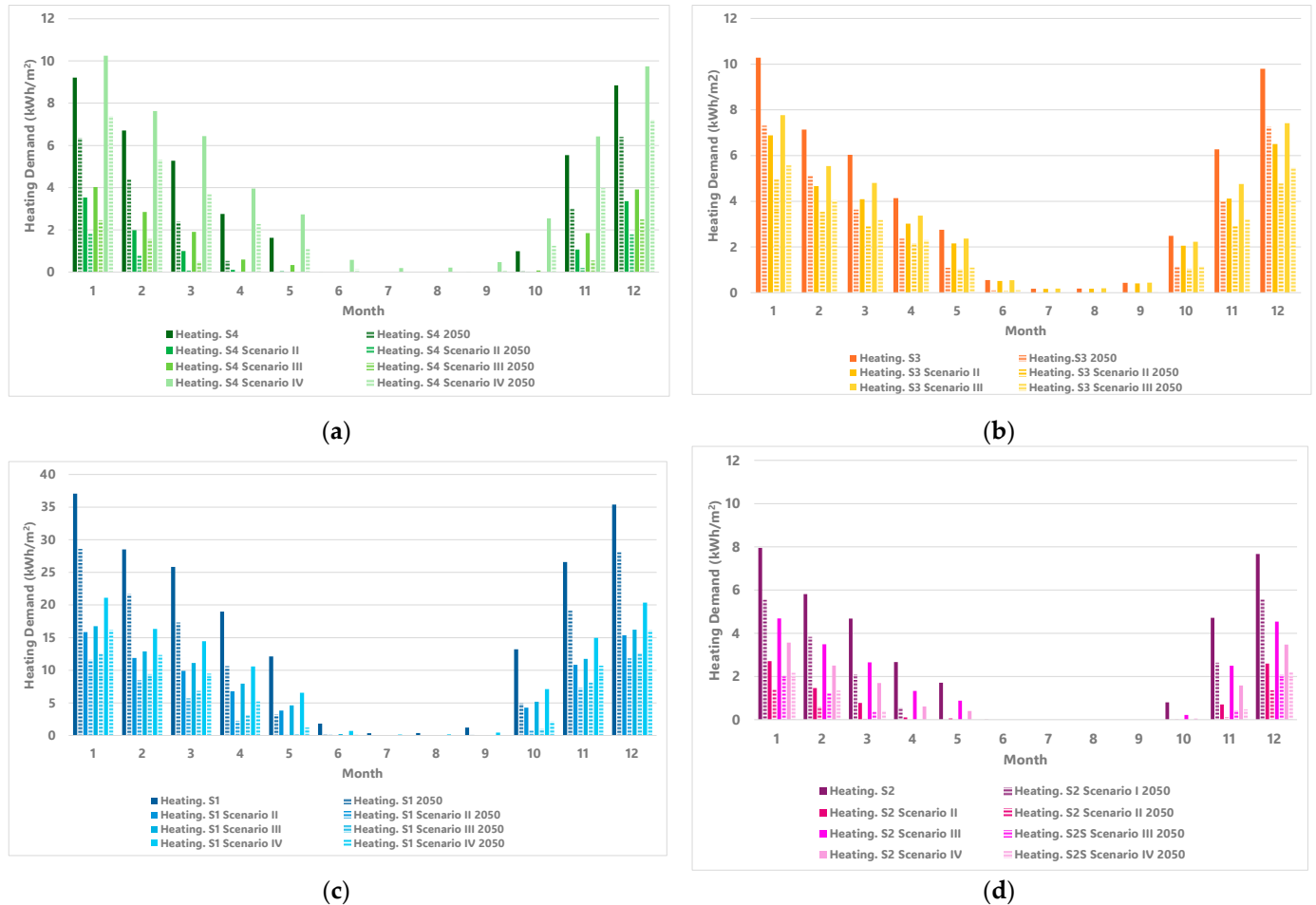


Figure A4. Monthly heating demands for each of the four school buildings, S4 (a), S3 (b), S1 (c), and S2 (d), in their current state, with the implementation of the proposed improvements in Scenarios II, III, and IV, and their respective projections under the 2050 climate change scenario. Own elaboration.

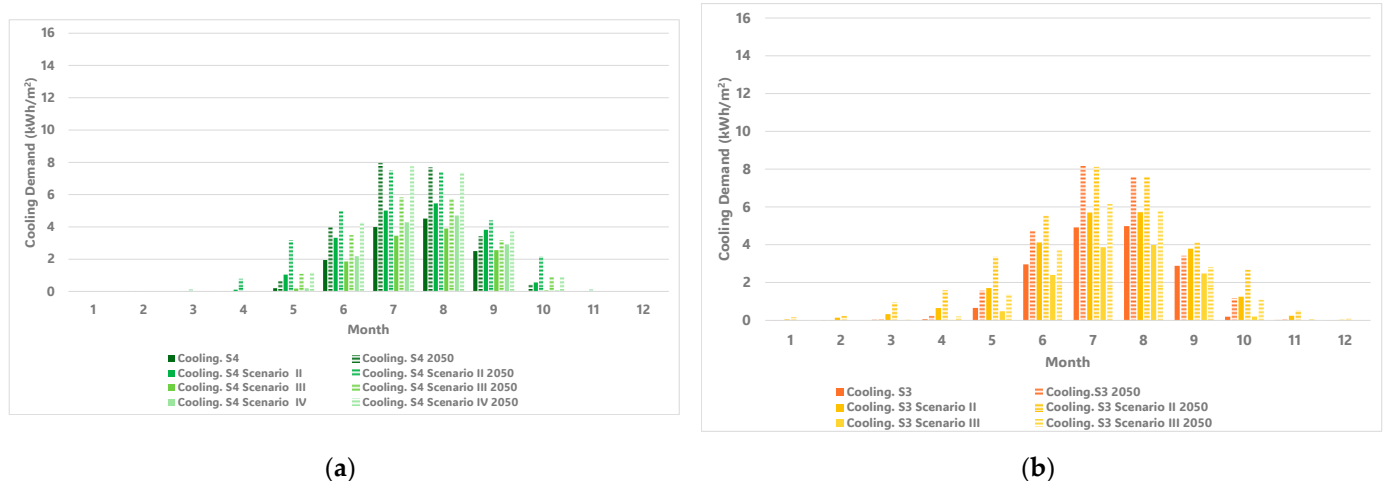


Figure A5. Cont.

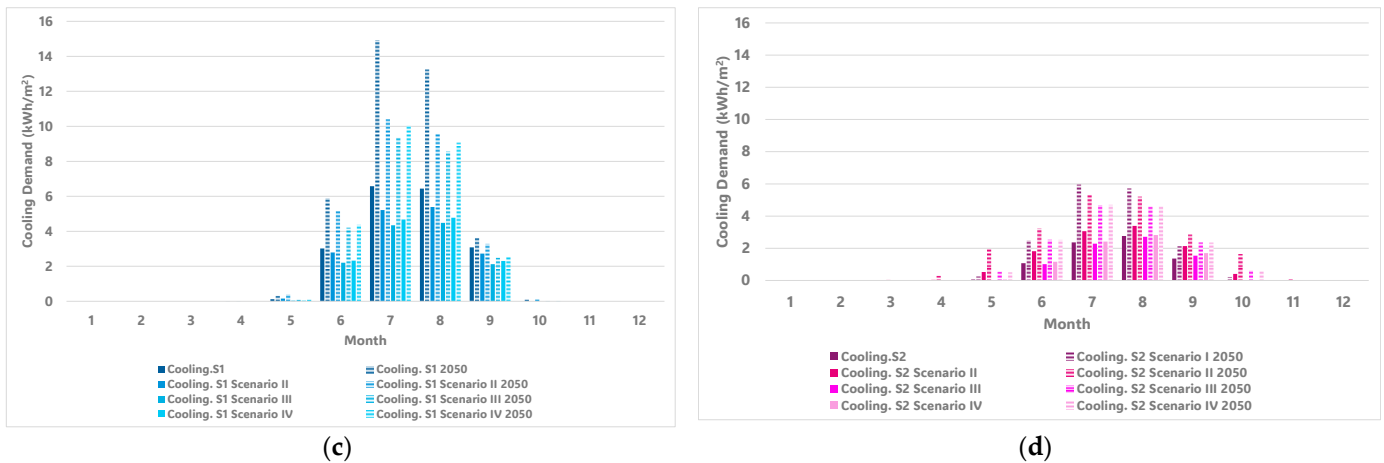


Figure A5. Monthly cooling demands for each of the four school buildings, S4 (a), S3 (b), S1 (c), and S2 (d), in their current state, with the implementation of the proposed improvements in Scenarios II, III, and IV, and their respective projections under the 2050 climate change scenario. Own elaboration.

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