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Assessing the Impact of Climate Changes, Building Characteristics, and HVAC Control on Energy Requirements under a Mediterranean Climate

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Abstract: Despite efforts to mitigate climate change, annual greenhouse gas emissions continue to rise, which may lead to the global warming of our planet. Buildings' thermal energy needs are inherently linked to climate conditions. Consequently, it is crucial to evaluate how climate change affects these energy demands. Despite extensive analysis, a comprehensive assessment involving a diverse range of building types has not been consistently conducted. The primary objective of this research is to perform a coherent evaluation of the influence of climate changes, construction element properties, and the Heating, Ventilation, and Air Conditioning (HVAC) system type of control on the energy requirements of six buildings (residential, services, and commercial). The buildings are considered to be located in a temperate Mediterranean climate. Our focus is on the year 2070, considering three distinct climatic scenarios: (i) maintaining the current climate without further changes, (ii) moderate climate changes, and (iii) extreme climate changes. The buildings are distributed across three different locations, each characterized by unique climatic conditions. Buildings' envelope features a traditional External Thermal Insulation Composite System (ETICS) and expanded polystyrene (EPS) serves as thermal insulation material. Two critical design factors are explored: EPS thickness ranging from 0 (no insulation) to 12 cm; and horizontal external fixed shading elements varying lengths from 0 (absence) to 150 cm. Six alternative setpoint ranges are assessed for the HVAC system control: three based on the Predicted Mean Vote (PMV) and three based on indoor air temperature (T_{air}). Results were obtained with a validated in-home software tool. They show that, even under extreme climate conditions, the application of thermal insulation remains energetically favorable; however, its relative importance diminishes as climate severity increases. Then, proper insulation design remains important for energy efficiency. The use of external shading elements for glazing (e.g., overhangs, louvers) proves beneficial in specific cases. As climate changes intensify, the significance of shading elements grows. Thus, strategic placement and design are necessary for good results. The HVAC system's energy consumption depends on the level of thermal comfort requirements, on the climate characteristics, and on the building's type of use. As climate change severity intensifies, energy demands for cooling increase, whereas energy needs for heating decrease. However, it is essential to recognize that the impact of climate changes on HVAC system energy consumption significantly depends on the type of building.

Keywords: climate change; buildings' energy requirements; HVAC control; buildings' thermal insulation; external solar shadings; buildings' type of use; Mediterranean climate; buildings climatization

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1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) report on climate change mitigation in 2022 [1] highlights significant trends in the global emissions of radiatively active substances (e.g., greenhouse gases (GHGs) and aerosols). Despite climate change mitigation efforts, annual greenhouse emissions grew on average by 2.2% per year from 2000 to 2019, compared with 1.3% per year from 1970 to 2000. Slightly different values for these emissions are reported on the Emissions Gap Report 2022 of the United Nations Environment Programme [2], where an average annual growth rate of 2.6% per year from 2000 to 2009 and 1.1% per year from 2010 to 2019 is reported. According to both reports, a peak was reached in 2019, followed by a decrease in 2020 due to COVID-19-related restrictions; it is also suggested that, in 2021, the level of total global emissions of GHGs and aerosols will be like, or even surpass, the 2019 level. According to the IPCC report [1], the building sector was responsible for 32% of the final energy consumption and 19% of the global equivalent of CO_2 emissions. These facts underscore the urgent need for sustainable practices and targeted policies to mitigate climate change and reduce emissions in the building sector.

1.1. Overview

Based on coherent and consistent assumptions about driving forces, such as demographic and socioeconomic development, technological change, energy consumption, and land use, the Intergovernmental Panel on Climate Change (IPCC) regularly presents plausible alternative forecasts for the future evolution of global emissions of radiatively active substances (e.g., greenhouse gases (GHGs) and aerosols) [3–5]. The likelihood of each emission scenario depends on the level of sustainability occurring in the global economy. Using these alternative emission forecasts, the IPCC has developed a series of "climate projections", which are commonly referred to as "climate scenarios".

In the second Assessment Report of the IPCC, published in 1996 [3], a set of alternative climate projections known as the "IS92 scenarios" was presented. Later, the IPCC Special Report on Emissions Scenarios [4] introduced the "SRES scenarios", comprising 40 distinct scenarios grouped into four families: A1, A2, B1, and B2. These scenarios vary in terms of their accumulated emissions and global warming potential. Specifically: SRES scenario families B1 and B2 can be considered to have a moderate impact; SRES scenario families A1 and A2 are associated with a high impact. Globally, these scenarios can be ordered from lowest to highest impact as follows: B1, B2, A1, A2.

In the fifth Assessment Report of the Intergovernmental Panel on Climate Change [5], four alternative scenarios for climate change are presented. These scenarios are known as Representative Concentration Pathways (RCP) and serve as critical tools for understanding and planning different future climates. Each RCP represents a different trajectory of GHGs emissions, shaped by various factors such as population size, economic activity, lifestyle, energy use, land use patterns, technology, and climate policy. They include a stringent mitigation scenario (RCP 2.6), two intermediate scenarios (RCP 4.5 and RCP 6.0), and one scenario with very high global emission of substances radiatively active (RCP 8.5).

- RCP 2.6 (stringent mitigation scenario): it assumes substantial and sustained reductions in GHGs emissions, representing a world where global efforts effectively limit climate change.
- RCP 4.5 (intermediate scenario): moderately reduced GHGs emissions reveal a future with some mitigation measures but are not as stringent as RCP 2.6.
- RCP 6.0 (intermediate scenario): it involves intermediate emission reductions and considers a world where climate action is taken, but not to the same extent as RCP 4.5.
- RCP 8.5 (high emissions scenario): it represents a future with very limited climate policies and very high global emissions of radiatively active substances, promoting a substantial environmental impact.

The land scenarios within the RCP framework offer a diverse range of potential futures, ranging from a net reforestation (RCP 2.6), some net reforestation (RCP 4.5), forestation similar to actual reality (RCP 6.0) and further deforestation (RCP 8.5). In terms of global emission of substances radiatively active and comparatively to present, scenario RCP 2.6 represents a future characterized by a substantial net reduction, scenario RCP 4.5 represents a future with some reduction, scenario RCP 6.0 represents a future with similar emissions, and scenario RCP 8.5 represents a future with a strong increase.

Relative to 1850–1900, global warming at the end of the 21st century (2081–2100) is projected to likely exceed 1.5 °C for RCP 4.5, RCP 6.0, and RCP 8.5 (high confidence), likely to exceed 2 °C for RCP 6.0 and RCP 8.5 (high confidence), more likely than not to exceed 2 °C for RCP 4.5 (medium confidence), but unlikely to exceed 2 °C for RCP 2.6 (medium confidence) [5].

The RCP scenarios cover a wider range of projections than SRES scenarios, as they also considered forecasts for land use and for climate policy. Globally, RCP 8.5 is broadly comparable to the SRES A2 scenario, RCP 6.0 to B2, RCP 4.5 to B1, and there is no equivalent scenario in SRES projections for RCP 2.6 [5].

1.2. State of the Art

Achieving good indoor environmental quality is crucial for promoting a pleasant sense of well-being and ensuring work efficiency [6,7]. Among the various factors that contribute to indoor environmental quality, thermal comfort stands out as particularly significant, even more so than visual and acoustic comfort or indoor air quality [8]. Furthermore, a substantial portion of a building's environmental impact results from energy consumption by the Heating, Ventilation, and Air Conditioning (HVAC) system [9,10]. Therefore, to minimize our ecological footprint, it is essential to maintain conditions of thermal comfort with low energy consumption.

The energy consumption of a building's air conditioning system—whether residential, commercial, or service-oriented—depends on several critical factors. These include the desired level of thermal comfort, the efficiency and type of control of the Heating, Ventilation, and Air Conditioning (HVAC) system, the building's architectural design and solar orientation, the characteristics of its passive construction elements, the thermal gains produced by the internal energy systems, the type of building occupancy, and the climatic conditions [7]. Moreover, given the extended lifespan of buildings (typically spanning 50–100 years), the likelihood of climate change occurring during their operational lifetime is substantial. Consequently, construction and refurbishment projects must account for sustainable operation in both the present and future climates [11–14].

Thermal comfort is influenced by both environmental conditions (such as air temperature, humidity, air velocity, and mean radiant temperature) and individual factors (including activity level and clothing characteristics) [15,16]. To maintain optimal thermal comfort indoors, HVAC systems adjust one or more parameters related to the thermal environment. The effectiveness of these systems hinges on two critical factors: equipment energy efficiency and the proficiency of the control system in ensuring thermal comfort and indoor air quality [7]. A wide variety of possibilities exists for HVAC control systems. The most common involves constraining environmental parameters within a specified range, without considering individual occupant factors [7,9]. Unfortunately, these procedures do not guarantee the desired thermal comfort quality and often result in higher energy consumption compared to occupant-based control methodologies [6,7,17,18].

The building characteristics that lead to the lowest value of energy demand for climatization strongly depends on the climate of the building location [10]. This holds true not only for extreme cold and hot climates but also for temperate regions, including the Mediterranean, where marked seasonal variations occur, with both cold and hot seasons [19], both necessitating HVAC systems to achieve indoor thermal comfort [9,10,20,21]. Consequently, the selection of the best constructive solutions for buildings located in these climates remains challenging.

The production of energy—whether thermal, mechanical, or electrical—from fuels, particularly fossil fuels, results in a significant emission of greenhouse gases (GHGs), which have a major impact on global warming [1,2]. This drawback can be mitigated by two primary approaches: producing energy from renewable sources and reducing overall energy consumption. Consequently, buildings must be designed to operate sustainably.

Achieving this goal involves minimizing energy usage while relying on renewable energy sources [11–14].

Energy consumption for air conditioning depends on the climate characteristics, the building's type of use, the quality of its passive and active constructive elements, the level of thermal comfort assured, and the HVAC system energy efficiency and the proficiency of its operation control [7,10,12], and represents a very significant portion of the building's energy consumption [22,23].

Buildings, whether new or existing, are significant energy consumers. Then, they must have an active role in mitigating climate change, namely by ensuring thermal comfort conditions with reduced energy consumption. Given their long lifespan—often exceeding 50 years [20]—it becomes imperative to identify solutions that reduce energy consumption by HVAC systems in buildings. This holds true for both current climatic conditions and possible alternatives (scenarios) arising from ongoing climate change.

1.3. Objectives and Scope

It is widely acknowledged that climate change will result in global warming [1,5,13]. Furthermore, a connection is predicted between the current climate characteristics and those anticipated due to climate change. Consequently, future climate scenarios for specific locations are typically derived from the present climate conditions at those sites [24–26], among others. Therefore, in studies like the one at hand, the current climate of the building's location holds relevance and must be taken into account.

It has been well-established that due to a warmer climate, the energy requirements for heating buildings will decrease, whereas the energy demands for cooling will rise [12,13,26,27], among others. The extent of the reduction in heating energy needs and the magnitude of the increase in cooling energy requirements depend on several factors, including the building's use, the characteristics of its passive and active construction elements, and the specific climate conditions. Consequently, this dynamic can lead to either an increase or a decrease in energy consumption for air conditioning. So, the main objective of this research is to conduct a comprehensive assessment of how climate changes, properties of construction elements, and the type of HVAC system control impact the energy requirements for climatization in a wide range of buildings (including residential, service, and commercial structures) placed in a Mediterranean climate.

The building stock comprises six types of structures: residential, including apartments within multifamily buildings and detached houses; service buildings with permanent occupancy, such as clinics; and service buildings with intermittent use, including schools and bank branches. Additionally, there is a commercial building, and a supermarket, which also has intermittent utilization.

All buildings share the same type of passive construction solutions, both opaque and glazed. As is often recommended for this type of construction, the opaque elements of the building envelope are equipped with a traditional External Thermal Insulation Composite System (ETICS) based on expanded polystyrene (EPS) material [10,20,28–31]. EPS thicknesses ranging from 0 (no insulating material) to 12 cm were tested, along with horizontal external fixed shading elements varying in length from 0 (absence) to 150 cm.

HVAC System and Setpoint Ranges: The HVAC system in all the buildings relies on a chiller/heat-pump with consistent performance coefficients. For the HVAC control system, six alternative setpoint ranges were assessed: three based on the Predicted Mean Vote (*PMV*), and three based on the indoor air temperature (T_{air}).

To accurately represent the temperate Mediterranean climate, the buildings were hypothetically situated in three distinct locations, each characterized by a different climate intensity: mild, moderate, and intense. This study considered the year 2070, and three climatic scenarios were assumed: (i) NCC—no further climatic changes (maintenance of the current climate); (ii) MRS—mid-range scenario (RCP 4.5), representative of medium-intensity climate changes; and (iii) HRS—high-range scenario (RCP 8.5), representing strong climate changes.

2. Research Objects

Six buildings, each with varying acclimatized areas, occupancy levels, internal thermal gains, and distinct types of use, were selected to represent the building stock: (i) an apartment at midlevel of a multi-story building; (ii) a detached house; (iii) a clinic with hospitalization; (iv) a high school; (v) a bank branch; and (vi) a medium-sized supermarket.

To enable meaningful comparisons between the various buildings, we assumed that they were all constructed using identical passive construction solutions (including opaque, glazed, and shading elements), and each one is equipped with a Heating, Ventilation, and Air Conditioning (HVAC) system that exhibits consistent seasonal energy performance.

2.1. Buildings' Main Characteristics and Occupancy

Table 1 provides a summary of the key characteristics of these buildings. The net and gross areas exclude non-acclimatized spaces. For further details about the layout and main features of these buildings can be found in the work by Raimundo et al. [20].

Table 1. Summary of the characteristics of the 6 buildings considered: *Np*—maximum number of occupants, *Nf*—number of floors, A_{cl}—acclimatized floor area, A_{gf}—gross floor area, *Ch*—ceiling height, *Vol*—acclimatized volume, A_{opc}—opaque area of external envelope, A_{glz}—glazed area of external envelope, *AR*—aspect ratio = $(A_{opc} + A_{glz})/Vol$, *EA*—envelope area ratio = $(A_{opc} + A_{glz})/A_{cl}$), *GA*—glazed area ratio = A_{glz}/A_{cl}.

	Apartment	Detached House	Clinic	High School	Bank Branch	Supermarket
Np [persons]	4	4	151	1100	12	194
Nf [--]	1	3	2	4	1	1
A_{cl} [m^2]	109.4	167.1	926.7	11,246.0	111.4	1035.3
A_{gf} [m^2]	141.6	212.6	1161.2	14,147.5	134.7	1176.1
Ch [m]	2.62	2.96	3.72	3.84	2.60	3.60
Vol [m^3]	286.6	494.6	3447.3	43,184.6	316.2	3727.1
A_{opc} [m^2]	58.6	343.4	743.4	22,703.8	181.0	2830.6
A_{glz} [m^2]	21.3	49.7	192.8	2975.3	37.2	96.6
AR [m^{-1}]	0.28	0.79	0.27	0.59	0.69	0.79
EA [--]	0.73	2.35	1.01	2.28	1.96	2.83
GA [--]	0.19	0.30	0.21	0.26	0.33	0.09

In general terms, occupancy and operating profiles exhibit the following characteristics:

- Across all buildings, occupancy and operating profiles vary based on the time of day, the day of the week, and the week of the year;
- When a building is unoccupied, the Heating, Ventilation, and Air Conditioning (HVAC) system remains off, and the lighting systems are either turned off or operate at very low power;
- Residential buildings are assumed to be unoccupied during the first fifteen days of August and permanently occupied during the remaining days of the year, by four people on Saturdays and Sundays, and between 6 P.M. and 8 A.M. on weekdays (Mondays to Fridays) and by one person the rest of the time;
- The clinic operates continuously throughout the year, with higher occupancy intensity between 8 A.M. and 8 P.M. on weekdays and on Saturdays;
- The school is only occupied between 8 A.M. and 6 P.M. on weekdays, it remains closed on Saturdays and Sundays and its operation follows the Portuguese academic calendar, so it operates at 100% during regular school periods; at 50% during the 1st examination phase (15–30 June); at 25% during the 2nd examination phase (1–15 July); at 25% during admission phase (16–31 July); and is closed during school holidays (the first 15 days of April, 1 to 31 August, and the last 15 days of December);

- The bank branch operates every weekday of the year and is occupied between 8 A.M. and 6 P.M., and it remains closed on Saturdays and Sundays;
- The supermarket operates every day of the year and it is occupied between 8 A.M. and 10 P.M., but with more intense activity on Saturdays and Sundays.

2.2. Opaque Elements of Buildings' Envelope

Each type of opaque construction element relies on a common base structure, consistent across all buildings and climates. The base structure most used in Portugal was assumed [20,32], which leads to buildings with substantial thermal inertia, a strategic choice for an effective mitigation of both overheating and cooling load peaks [10,13]. Table 2 outlines the base structure details for the opaque elements in contact with the exterior, including their thickness, useful thermal mass (*Mt*), and thermal transmission coefficient (*U*).

Table 2. Base structure of some opaque elements of the external envelope.

Element	Description (from Outside to Inside)	Values
Wall	Traditional plaster with 2 cm, bored brick of 22 cm, not-ventilated air space with 1 cm, bored brick of 11 cm, traditional plaster with 2 cm	*Thickness* = 38 cm Mt = 150 kg/m^2 U = 0.88 W/(m^2 K)
Pillar/Beam	Traditional plaster with 2 cm, inert reinforced concrete (iron volume less than 1%) with 22 cm, not-ventilated air space of 1 cm, bored brick of 11 cm, traditional plaster with 2 cm	*Thickness* = 38 cm Mt = 150 kg/m^2 U = 1.36 W/(m^2 K)
Floor above outside	Traditional plaster with 2 cm, lightened slab of 38 cm, light-sand concrete of 7.5 cm, screed (mortar) of 5.5 cm, oak wood with 2 cm	*Thickness* = 55 cm Mt = 150 kg/m^2 U = 1.17 W/(m^2 K)
Ground floor	Waterproofing layer, lightened slab of 38 cm, light-sand concrete of 7.5 cm, screed (mortar) of 5.5 cm, oak wood with 2 cm	*Thickness* = 54 cm Mt = 150 kg/m^2 U = 1.23 W/(m^2 K)
Accessible roof	Mosaic tile with 1 cm, screed (mortar) of 5.5 cm, waterproofing of 3 mm, light-sand concrete of 7.5 cm, lightened slab of 38 cm, traditional plaster with 2 cm	*Thickness* = 55 cm Mt = 150 kg/m^2 U = 1.39 W/(m^2 K)
Not accessible roof	Sandstone (inert) with 4 cm (or ceramic tile), waterproofing of 3 mm, screed (mortar) of 4 cm, lightened slab of 23 cm, traditional plaster with 2 cm	*Thickness* = 33 cm Mt = 150 kg/m^2 U = 2.40 W/(m^2 K)

The basic structure of each opaque construction element is enhanced by the application of expanded polystyrene (EPS) on the outer surface through an External Thermal Insulation Composite System (ETICS), often recognized as an efficient solution in terms of energy demands [10,20,28–31]. An additional advantage is its versatility, as it can be employed in both new constructions and building refurbishments. EPS thermal insulation material was chosen due to its economic and environmental benefits, its integrability into nearly all opaque elements, and its durability of at least 50 years [10,20,29].

EPS thicknesses ranging from 0 cm (without insulation) to 12 cm were tested, representing the economically viable range for buildings situated in temperate Mediterranean climates [10,20]. As an example, Table 3 displays the thermal transmission coefficient (*U*) values for the more relevant opaque elements of the external envelope, corresponding to different EPS thicknesses. Like the buildings, these values have already been considered in previous works [7,10,20]. Notably, the impact on the *U* value diminishes as the thickness of thermal insulation increases.

Table 3. Thermal transmission coefficient [W/(m^2 K)] of some opaque elements of the external envelope as function of EPS thicknesses.

EPS Thickness [cm]	Thermal Transmission Coefficient—*U* [W/(m^2 K)]					
	Wall	Pillar/Beam	Floor above Outside	Ground Floor	Accessible Roof	Non-Accessible Roof
0	0.88	1.36	1.17	1.23	1.39	2.40
1	0.72	1.01	0.90	0.94	1.03	1.49
2	0.62	0.83	0.75	0.78	0.84	1.12
3	0.54	0.69	0.64	0.65	0.70	0.88
4	0.48	0.59	0.56	0.57	0.60	0.73
5	0.43	0.52	0.49	0.50	0.52	0.62
6	0.39	0.46	0.44	0.45	0.47	0.54
7	0.36	0.42	0.40	0.41	0.42	0.49
8	0.33	0.38	0.36	0.37	0.38	0.43
9	0.30	0.34	0.33	0.33	0.34	0.38
10	0.28	0.32	0.30	0.31	0.32	0.35
11	0.26	0.29	0.28	0.28	0.29	0.32
12	0.25	0.28	0.27	0.27	0.28	0.30

2.3. Glazing Elements

The glazing system identified by Raimundo et al. [33] as the most economically advantageous for buildings located in Portugal was selected. The windows incorporate an aluminum frame with thermal barrier and double glazing (colorless of 6 mm + 11 mm air-layer + colorless of 4 mm), and they are externally protected by blinds made of horizontal plastic strips. This glazing system has a thermal transmission coefficient (U) and a solar factor ($g_{\perp}$) of U_{w} = 3.05 W m^{-2} K^{-1} and $g_{\perp \mathrm{w}}$ = 0.79 when the blind element is not active and of U_{wp} = 1.56 W m^{-2} K^{-1} and $g_{\perp \mathrm{wp}}$ = 0.05 when it is active.

2.4. External Fixed Shading Elements

Likely, climate change will lead to an increase in both the outside air temperature and the intensity of solar radiation [1,4,5], and, consequently, buildings will experience reduced energy requirements for heating and increased energy demands for cooling [12,26,27], among others. To reduce cooling needs without compromising natural interior lighting, an effective strategy is the implementation of external horizontal glazing shading systems [34–37].

Despite the existing glazing areas in the current architecture (referred to as the base architecture) being partially shaded by building elements such as balconies and facade cutouts, an assessment was conducted to evaluate the impact of installing horizontal external fixed shading elements on air conditioning energy consumption. However, the application of additional shades was only considered for glazing areas not already shaded by elements of the base architecture or when such shading had minimal relevance. Additionally, given the buildings' location in the northern hemisphere, no additional shading elements were considered for glazing oriented toward east-northeast, north, or west-northwest.

If present, all additional external fixed horizontal shading elements are positioned at the top of the respective window and have the same length, and shade lengths ranging from 0 cm (no shade) to 150 cm, in increments of 10 cm, have been tested. It is important to recognize that whereas external fixed glazing shades have the potential to reduce cooling energy demands, they may also increase heating energy requirements. Consequently, the energy impact of installing fixed glazing shades depends on the building's use type and the prevailing climate conditions.

2.5. Heating, Ventilation, and Air Conditioning System

In temperate Mediterranean climates, buildings rely on both heating and cooling systems to maintain thermal comfort. Among the available options, electric air-source heat pumps demonstrate reasonable performance in heating mode. Consequently, systems based on air-source chiller/heat pumps are commonly chosen [7,20,32]. Therefore, these are the Heating, Ventilation, and Air Conditioning (HVAC) systems considered. The indoor air renewal is ensured by Air Handling Units (AHUs) and/or air-extraction fans, both operating at an efficiency of 70% [7,20].

The HVAC systems are assumed to be equipped with a chiller/heat-pump classified as European class A+ [38], as it aligns with the equipment commonly installed in practice. The chiller has a seasonal energy efficiency ratio *SEER* = 5.85 in cooling mode and the heat-pump has a seasonal coefficient of performance *SCOP* = 4.30 in heating mode [7,10,38].

3. Methods and Conditions

The present study relies on a numerical assessment of the relationship between energy demand and consumption for air conditioning with the level of thermal comfort indoors, the building's type of use, the building's passive and active construction elements, and the climate specificities, considering alternative scenarios of climate change.

3.1. Calculation Tool

The version 5.07 of SEnergEd software [7,10,20,33], a validated in-home tool developed for research purposes, was employed in this study. This user-friendly software integrates algorithms for dynamically simulating the thermal and energy behavior of various building types (residential, commercial, and service). Its capabilities include assessing thermal comfort, analyzing environmental impact, and evaluating the economic aspects of a building's life cycle.

This software predicts the thermal behavior of buildings using a reformulated version of the dynamic hourly model known as 5R1C (which stands for five thermal resistances and one thermal capacitance) described in ISO 13790 [39]. The thermal behavior and energy needs are conditioned by the maximum useful capacity of the HVAC system installed in the building. Energy demands from other equipment and systems (such as domestic hot water, lighting, and appliances) are calculated dynamically based on their hourly operating profiles and installed power. By considering the energy performance of the equipment and systems, the energy demands are then converted into actual consumption.

The operation of the HVAC system can be controlled using either indoor air temperature (T_{air}) setpoints or predicted mean vote (*PMV*) setpoints [15,16]. Additionally, both control strategies incorporate an additional setpoint for air relative humidity (*RH*). This procedure is carried out following a predictive control algorithm model. In addition to the control by setpoints and with the ability to override them, hourly operating profiles of HVAC systems can be defined.

Further details about the SEnergEd software can be found elsewhere [7,10,20,33].

3.2. Control of the Climatization System Operation

According to standards ASHRAE 55:2004 [15] and ISO 7730:2005 [16], the predicted mean vote (*PMV*) is determined based on the overall thermal balance of the human body. Its absolute value correlates with the percentage of people who experience thermal discomfort, more specifically, *PMV* = 0 indicates thermal comfort, *PMV* < 0 means discomfort due to cold, and *PMV* > 0 is discomfort due to heat. The calculation of *PMV* value requires the knowledge of four environmental parameters (air temperature, air humidity, air velocity, and mean radiant temperature) and of three individual factors (clothing intrinsic insulation, metabolic rate, and external work).

In each hourly time-step, the SEnergEd software computes the following parameters within the thermal zone: air temperature, humidity, and mean radiant temperature. Then, the clothing's intrinsic thermal insulation, the person's physical activity and external work, and the air's velocity must be provided as input parameters. The values considered in this study for these parameters, typical of habits in Mediterranean temperate climates, are shown in Table 4. These values vary based on the building's type of use, the season of the year, and whether it is daytime or nighttime.

Table 4. Intrinsic clothing insulation, activity level, and indoor air velocity.

	During the:	During the:	Intrinsic Clothing Insulation [clo]	Activity Level [met]	Air Velocity [m/s]
Apartment and Dwelling	Winter	Day/Night	1.3/2.6	1.2/0.8	0.2
	Spring and Autumn	Day/Night	1.0/2.0		
	Summer	Day/Night	0.7/1.4		
Clinic	Winter	Day/Night	1.3/2.0	1.4/0.8	0.2
	Spring and Autumn	Day/Night	1.0/2.0		
	Summer	Day/Night	0.7/1.4		
School	Winter	Day	1.3	1.4	0.3
	Spring and Autumn	Day	1.0		
	Summer	Day	0.7		
Bank branch	Winter	Day	1.4	1.2	0.2
	Spring and Autumn	Day	1.2		
	Summer	Day	1.0		
Supermarket	Winter	Day/Night	1.5/1.5	1.5/1.5	0.3
	Spring and Autumn	Day/Night	1.2/1.2		
	Summer	Day/Night	0.7/0.7		

Six possibilities for the operation of the HVAC system were considered. In three of them, the control was performed by setpoints of the predicted mean vote ($PMV_{\text{min}} \leq PMV \leq PMV_{\text{max}}$) and in the other three, this control is performed by air temperature setpoints ($T_{min} \leq T_{air} \leq T_{max}$). A control with air relative humidity setpoints ($RH_{min} \leq RH \leq RH_{max}$) was associated with both controls (in the present study RH was maintained between 50 and 70%). In addition to the control by setpoints, and with the ability to override them, hourly operating profiles were defined.

Table 5 outlines the six possibilities considered for HVAC system control, along with the hypothesis of the non-existence of an HVAC system (NHS). A, B, and C represent PMV setpoints, separated by increments of 0.25. The three T_{air} setpoints are labeled as DT1, DT3, and DT5, where DT1 represents a temperature difference between the upper and lower limits of 1 °C, DT3 of 3 °C, and DT5 of 5 °C, respectively. In the case of the bank branch and the supermarket, the setpoint values of T_{air} are slightly lower than the corresponding ones for the other buildings, since it was considered that the occupants of those buildings usually wear clothing with higher thermal insulation.

The setpoint limits considered for both PMV and T_{air}, as shown in Table 5, are based on the endorsements outlined in the standard EN 16798-1 [40], which provides specific conditions that must be met in buildings to achieve defined levels of indoor environmental quality. Controls A and DT1 guarantee the highest quality of thermal comfort and align with the Category I level of this standard, recommended for spaces occupied by fragile individuals or those with special requirements. Controls B and DT3 counterpart Category II, endorsed for buildings to be used by people without special requirements, but with high expectations. Controls C and DT5 fall under Category III, suggested for spaces with moderate expectations. NHS concerns the situation where the building lacks an HVAC system.

Table 5. Types of control of operation of the buildings' climatization system.

Control	Control of HVAC System		
Type	**Apartment, Dwelling, Clinic, School, Bank Branch, and Supermarket**		
A	$-0.25 \leq PMV \leq +0.25$		$PPD \leq 6.3\%$
B	$-0.50 \leq PMV \leq +0.50$		$PPD \leq 10.2\%$
C	$-0.75 \leq PMV \leq +0.75$		$PPD \leq 16.8\%$
NHS	No HVAC system		
	Apartment, Dwelling, Clinic, and School	**Bank Branch**	**Supermarket**
DT5	$20 \leq T_{air} \leq 25$ °C	$19 \leq T_{air} \leq 24$ °C	$18 \leq T_{air} \leq 23$ °C
DT3	$21 \leq T_{air} \leq 24$ °C	$20 \leq T_{air} \leq 23$ °C	$19 \leq T_{air} \leq 22$ °C
DT1	$22 \leq T_{air} \leq 23$ °C	$21 \leq T_{air} \leq 22$ °C	$20 \leq T_{air} \leq 21$ °C

3.3. Climate Scenarios

Research related to the thermal energy demand of buildings often relies on simulation tools, which necessitate a file containing a year's worth of hourly climate data specific to the building's location. Subsequently, to assess the impact of climate change on the thermal and energy behavior of buildings, appropriately prepared climate data files are essential. There are two primary approaches for creating these files: one involves predictions based on historical data, whereas the other relies on fundamental physical models [25]. In this study, we employ the historical model to generate the required hourly climate dataset files. For this, the "morphing procedure" proposed by Belcher and colleagues was used [24]. This approach involves generating future design weather data by adjusting present-day climate data using "correction coefficients" derived from "global climatic models" tailored to specific climate change scenarios. To derive the correction coefficients, the global climate model CGCM3.1/T47, developed by the "Canadian Center for Climate Modeling and Analysis" [41] was employed, which generates values for nearly all geographical locations on the planet, with a resolution of $3.75° \times 3.75°$.

The morphing of each individual weather parameter is accomplished using three alternative algorithms [24,25]: shifting, linear stretching (scaling factor), and a combination of both (shifting and stretching). The shifting method relies on an absolute change in the monthly mean value of the variable, and it is employed when a change in the mean is predicted for that specific weather parameter in that given climate change scenario. The linear stretching is used when a proportional change to either the mean or the variance of the individual weather parameter is predicted in that climate change scenario; for instance, this approach is suitable for variables like solar radiation, which becomes zero at night. A combination of shift and stretch is applied in cases where both the mean and variance of an individual weather parameter are expected to change (e.g., air temperatures), reflecting changes in average, minimum, and maximum daily values. Deeper details about the mathematical operations involved in the "morphing procedure" can be found in Belcher et al.'s paper [24].

To generate files for future climate scenarios based on the current climate, adjustments were made only to the values of dry bulb temperature, relative humidity, and direct, global, and diffuse solar radiation. The values of the components of solar radiation were obtained using the scale factor morphing procedure (linear stretching), ensuring that the solar radiation values align with the projected changes. The dry bulb temperature at each hour of each month was determined using a combination of the morphing procedures shifting and stretching, which led to changes in average, minimum, and maximum daily values. Unfortunately, the global climate model used (CGCM3.1/T47) does not provide predictions for the correction coefficient needed to obtain relative humidity. However, it does offer predictions for specific humidity [41]. Therefore, to derive the relative humidity of the considered future climate scenarios, it was necessary to first obtain the corresponding specific humidity values and then convert them into relative humidity using appropriate methods. The specific humidity value for each hour of each month was obtained using the linear stretching methodology.

The buildings (residential, services, and commercial) under consideration are hypothetically situated in a temperate Mediterranean climate. This climate type spans an extensive range of countries (including Greece, Italy, Portugal, Spain, Turkey), and several specific regions (such as parts of Albania, Australia, France, South Africa, and California). Temperate climates strike a balance: they are neither excessively hot in summer nor too cold in winter, and they avoid extreme dryness or excessive humidity. Despite this moderation, these climates exhibit substantial temperature differences between day and night, and present marked climatic variations across different seasons. The Köppen–Geiger climate classification designates these temperate Mediterranean climates as *Csa* or *Csb* [12,30].

Significant climatic disparities exist across regions within temperate Mediterranean climates (referred to here as MC) [7,19]. To accurately represent these climates, we hypothetically position buildings in three distinct locations, each characterized by different weather patterns. These locations correspond to the following MC types: (i) mild in winter and mild in summer (MC1); (ii) moderate in winter and moderate in summer (MC2); and (iii) intense in winter and intense in summer (MC3). The locals selected to represent these climate types are all located in Portugal and are Funchal (at an elevation above sea level $Z = 415$ m) for mild climate MC1; Ansião ($Z = 361$ m) for moderate climate MC2; and Mirandela ($Z = 600$ m) for intense climate MC3. These carefully selected localities provide a comprehensive snapshot of the diverse climatic variations within the temperate Mediterranean regions.

In this analysis, the year 2070 is considered and three distinct climate change scenarios are explored as follows: (i) no further climate changes (NCC); a mid-range scenario (MRS); and a high-range scenario (HRS). The NCC scenario assumes that the current climate remains unchanged, with no additional alterations beyond the existing climatic conditions. The MRS scenario represents medium-intensity climate changes, as projected by the IPCC Representative Concentration Pathway RCP 4.5 [5], representing some impact on climate, affecting ecosystems, weather patterns, and global temperatures. The HRS scenario emerges from extreme climate changes, as forecasted by the IPCC scenario RCP 8.5, and represents a severe impact on climate.

Various methodologies exist for classifying the different climate types. Among these, the approach based on heating degree days(HHD [°C·day/year]) and cooling degree days(CDD [°C·day/year]) provides a more direct link between outdoor weather conditions and energy requirements for heating and cooling, respectively [7,30,42].

In this study, the HDD and CDD values are defined with respect to reference temperatures of 20 °C and 25 °C, respectively, and are accordingly referred to as HDD_{20} and CDD_{25}. Their values for the three temperate Mediterranean climate types selected (MC1, MC2, MC3) and the three climate change scenarios considered (NCC, MRS, HRS) are summarized in Table 6. The corresponding annual average values of air temperature T_m (and its difference to the NCC scenario ΔT_m), of air relative humidity RH_m (and its difference to the NCC scenario ΔRH_m), and of horizontal global solar radiation $HGSR_m$ (and its difference to the NCC scenario $\Delta HGSR_m$) are also presented in Table 6.

Figure 1 displays boxplot graphs that provide a global overview of the climate predictions for the year 2070, for the three types of temperate Mediterranean climate selected (MC1, MC2, MC3) and the three climate change scenarios considered (NCC, MRS, HRS). As they are the most indicative, the values of air temperature, relative humidity, and global solar radiation incident on a horizontal plane are presented in this figure. In each case shown, the lower line indicates the minimum value, the bottom line of the box the first quartile (25th percentile), the line inside the box the median, the marker inside the box the mean, the top edge of the box the third quartile (75th percentile) and the upper line the maximum value.

Table 6. HDD_{20} and CDD_{25} values [°C·day/year] and annual average values of air temperature T_m (and its difference to the NCC scenario, ΔT_m) [°C], of air relative humidity $RH_{\rm m}$ (and its difference to the NCC scenario, ΔRH_m) [%], of horizontal global solar radiation $HGSR_{\rm m}$ (and its difference to the NCC scenario, $\Delta HGSR_m$) [W/m^2], of maximum difference in air temperature during the year $\Delta T_{\max}$ (= $T_{\max} - T_{\min}$) [°C], and of average values of air temperature T_m (and its difference to the NCC scenario, ΔT_m) [°C] for the stations of the year, for the temperate Mediterranean climate types selected and the climate change scenarios considered.

Climate Type		NCC	MRS (RCP 4.5)	HRS (RCP 8.5)
MC1	HDD_{20}	1256	682	456
Mild	CDD_{25}	16	72	148
	T_m (ΔT_m)	17.0 (--)	18.4 (+1.4)	19.4 (+2.4)
	RH_m (ΔRH_m)	76 (--)	79 (+3)	74 (−2)
	$HGSR_m$ ($\Delta HGSR_m$)	284 (--)	328 (+44)	329 (+45)
	$\Delta T_{\max}$	19.6	11.7	11.1
MC2	HDD_{20}	2111	1732	1357
Moderate	CDD_{25}	81	134	257
	T_m (ΔT_m)	15.1 (--)	16.5 (+1.4)	18.3 (+3.2)
	RH_m (ΔRH_m)	73 (--)	72 (−1)	69 (−4)
	$HGSR_m$ ($\Delta HGSR_m$)	317 (--)	361 (+44)	362 (+45)
	$\Delta T_{\max}$	29.9	26.7	28.6
MC3	HDD_{20}	2762	2170	1739
Intense	CDD_{25}	144	152	276
	T_m (ΔT_m)	13.6 (--)	15.3 (+1.7)	17.0 (+3.4)
	RH_m (ΔRH_m)	69 (--)	72 (+3)	74 (+5)
	$HGSR_m$ ($\Delta HGSR_m$)	305 (--)	323 (+18)	336 (+31)
	$\Delta T_{\max}$	35.9	28.4	30.0
MC1 + MC2 + MC3	Winter	10.6 (--)	12.6 (+2.0)	13.7 (+3.1)
T_m (ΔT_m)	Spring	15.2 (--)	15.7 (+0.5)	17.0 (+1.8)
	Summer	20.7 (--)	22.2 (+1.5)	24.2 (+3.5)
	Autumn	14.3 (--)	16.3 (+2.0)	17.9 (+3.6)

As depicted in Table 6, both the values of HDD_{20} (heating degree days at 20 °C) and CDD_{25} (cooling degree days at 25 °C) increase as the severity of the present climate intensifies. However, their behavior diverges based on the impact of climate change. The value of HDD_{20} decreases as climate change becomes stronger. Conversely, the value of CDD_{25} rises with increasing of climate change intensity. These trends highlight the relationship between climate severity, ongoing climate changes, and temperature-related energy demands.

The global climate forecasts, as depicted in Table 6 and Figure 1, indicate an increase in the average air temperature (T_m) with the escalation of climate change intensity. Additionally, climate change alters temperature patterns throughout the year, affecting both the maximum temperature difference ($\Delta T_{\max} = T_{\max} - T_{\min}$), and the average air temperatures across seasons. Relatively to the NCC scenario, climate change leads to a decrease of $\Delta T_{\max}$, which is more pronounced in the MRS scenario than in the HRS one. The average values of air temperature T_m reveal that in the present climate (NCC scenario), the coldest season of the year is winter, followed by autumn, spring, and summer (the hottest). In the situation of further climate change, the order will be winter, spring, autumn, and summer, and all stations of the year will warm up with the increase in climate change intensity, but not in a uniform way. The station less affected by climate change will be the spring and the most affected will be the autumn. These predictions also highlight that there will be no substantial alteration in relative humidity values, and a definitive relationship between these values and climate change intensity remains elusive. Regarding horizontal global solar radiation, an elevation in the corresponding value is anticipated as climate change severity intensifies. Notably, the variation in the average value of horizontal global solar radiation ($HGSR_m$) is significant when transitioning from the NCC scenario (no further climatic changes) to the MRS (mid-range scenario, RCP 4.5), but less pronounced when moving from MRS to HRS (high-range scenario, RCP 8.5).

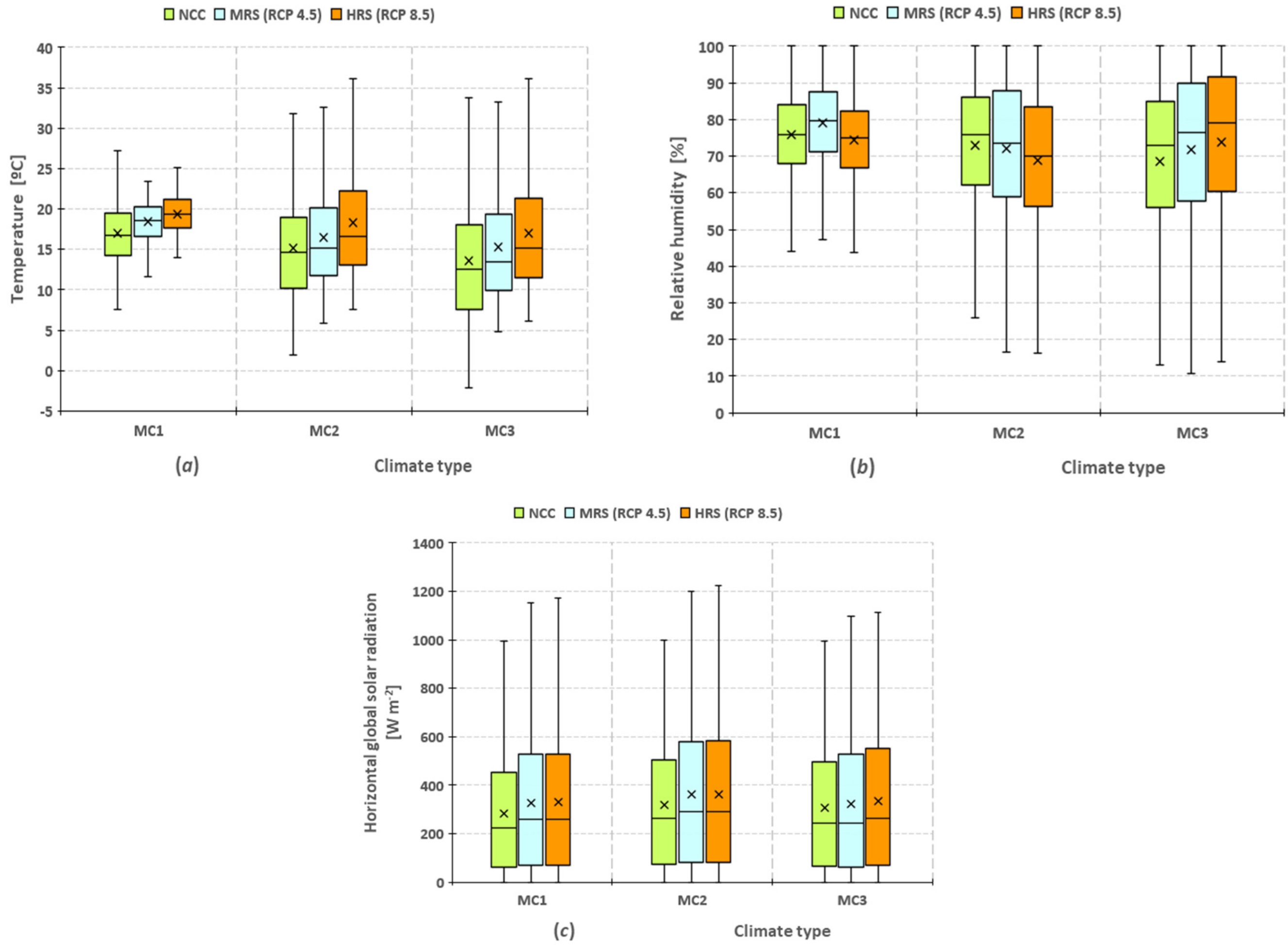

Figure 1. Boxplot representation of the climate in 2070, for the three Mediterranean climates selected (MC1, MC2, MC3) and the three climate change scenarios considered (NCC, MRS, HRS), by (**a**) air temperature, (**b**) relative humidity, and (**c**) global solar radiation on a horizontal plane.

In Table 6, considering the mild climate MC1, the average air temperature (T_m) exhibits the values of 17.0 °C for the NCC scenario, of 18.4 °C for the MRS scenario, and of 19.4 °C for the HRS scenario. The average horizontal global solar radiation ($HGSR_m$) values are 284 W/m^2 for NCC, 328 W/m^2 for MRS, and 329 W/m^2 for HRS. Taking the NCC scenario as reference, we observe an increase in average air temperature (ΔT_m) of +1.4 °C in the MRS scenario and of +2.4°C in the HRS one. Additionally, climate change leads to a decrease in the maximum difference in air temperature during the year ($\Delta T_{\max}$) of 7.9 °C for the MRS and of 8.5°C for the HRS. The change in $HGSR_m$ ($\Delta HGSR_m$) is of +44 W/m^2 for MRS and of +45 W/m^2 for HRS.

In the context of the moderate MC2 climate, Table 6 reveal average air temperatures (T_m) of 15.1 °C for the NCC scenario, of 16.5°C for the MRS scenario, and of 18.3 °C for the HRS scenario. The average horizontal global solar radiation ($HGSR_m$) exhibits the values of 317 W/m^2 for NCC, of 361 W/m^2 for MRS, and of 362 W/m^2 for HRS. Comparing these values to the NCC reference, we note an increase of ΔT_m = +1.4 °C in the MRS case and a more substantial rise of ΔT_m = +3.2 °C in the HRS case. Climate change leads to a decrease in the maximum difference in air temperature during the year ($\Delta T_{\max}$) of 3.2 °C for the

MRS and of 1.3 °C for the HRS. The change in $HGSR_m$ amounts to $\Delta HGSR_m$ = +44 W/m^2 in the MRS and $\Delta HGSR_m$ = +45 W/m^2 in the HRS.

For the intense climate MC3, Table 6 reveals the values of T_m = 13.6 °C for the NCC scenario, 15.3 °C for the MRS scenario, and 17.0 °C for the HRS scenario. In this type of climate, $HGSR_m$ = 305, 323, and 336 W/m^2 for the NCC, MRS, and HRS scenarios, respectively. Comparing previous values with the NCC reference, we observe an increase of ΔT_m = +1.7 °C in the MRS scenario and a more substantial rise of ΔT_m = +3.4 °C in the HRS one. Climate change leads to a decrease in the maximum difference in air temperature during the year ($\Delta T_{\max}$) of 7.5 °C for the MRS and of 5.9 °C for the HRS. The change in $HGSR_m$ amounts to $\Delta HGSR_m$ = +18 W/m^2 in the MRS and $\Delta HGSR_m$ = +31 W/m^2 in the HRS.

To assess whether the differences between scenarios are statistically significant, we employed a Student's *t*-test, considering a two-tailed distribution and two samples with unequal variance. Probabilities associated with this test were calculated for three key parameters: air temperature (T_{air}), relative humidity (*RH*), and horizontal global solar radiation (*HGSR*). Relative to the present climate (scenario NCC), the other two (mid-range (MRS) and high-range (HRS)), show a significant statistical difference ($p < 0.001$) for the three previous parameters (T_{air}, *RH*, and *HGSR*) in the three Mediterranean climates (mild (MC1), moderate (MC2), and intense (MC3)). The difference is also statistically significant ($p < 0.001$) between MRS and HRS scenarios for the parameters T_{air} and *RH*, but not for *HGSR* ($p > 0.05$).

4. Results and Discussion

The energy perspective was employed to assess the relation between the thickness of thermal insulation and the length of horizontal external fixed glazing shades with the building type, the type of control of the Heating, Ventilation, and Air Conditioning (HVAC) system, and the severity of climate change. For this, three climate change scenarios projected for the year 2070 (NCC—no further climate changes, MRS—mid-range scenario, and HRS—high-range scenario), and six different buildings located in temperate Mediterranean climates (an apartment, a detached house, a clinic, a school, a bank branch, and a supermarket) were considered. The energy perspective considered includes only the operational energy, without accounting for embodied energy on materials or energy associated to buildings' end-of-life. Then, "energy demand" and "energy needs" refer to the "operational useful annual thermal energy" requirement for heating or for cooling, and "energy consumption" refers to "operational energy consumption by the HVAC system (electric energy) during an entire year".

The results presented in the subsequent sections are normalized per square meter (m^2) of the acclimatized spaces' floor area. Table 1 provides details on the net (A_{cl}) and gross (A_{gf}) floor areas of the buildings. As previously indicated in Table 5, six alternatives for HVAC system control were explored. These alternatives include three by predicted mean vote (*PMV*) setpoints (labeled as A, B, and C), and three by indoor air temperature (T_{air}) setpoints (labeled as DT1, DT3, and DT5). "A" corresponds to $-0.25 \leq PMV \leq +0.25$, "B" to $-0.50 \leq PMV \leq +0.50$, "C" to ($-0.75 \leq PMV \leq +0.75$), "DT1" to a temperature difference between the upper and lower limits of 1 °C, "DT3" represents a difference of 3 °C, and "DT5" reflects a difference of 5 °C. Furthermore, the non-existence of an HVAC system (NHS) was accounted for.

This study involves a total of 67,392 cases (=16 shading lengths × 13 insulation thickness × 6 buildings × 3 climate change scenarios × 3 locations × 6 HVAC setpoint types). To handle this large number of cases efficiently, the following strategy was implemented: (1st) The in-home software was prepared to simulate the 3 climate change scenarios, the 3 locations and the 6 HVAC setpoint types in each run (1 run → simulation of 54 cases); (2nd) the simulations were conducted in two rounds (which reduces the cases considered to 9396): identification of the optimal thermal insulation thickness for buildings without additional shading (78 runs → 4212 cases); and 2nd round-identification of the optimal shading length only for buildings with the optimal thermal insulation thickness (96 runs $\rightarrow$ 5184 cases). With this strategy, it was necessary to prepare and make only 174 runs.

4.1. Optimal Thermal Insulation Thickness and External Shade Lengths

Achieving the right balance between insulation thickness, shade length, and HVAC control is crucial for maximizing energy efficiency while ensuring occupant comfort. Each building type, climate type, and climate change scenario requires tailored solutions.

The optimal thermal insulation thickness and glazing shade length depend on the specific perspective: energy efficiency, environmental impact, or economic cost. This issue has been already addressed by Raimundo's team [10,20], where the same buildings and locations were considered, but only for the present climate (NCC scenario). In the present work, only the energy perspective was considered.

In energy terms, the optimal values for thermal insulation thickness of the opaque elements of the building envelope and the length of external shades are those that result in the lowest energy consumption for climatization (both heating and cooling). The corresponding values were determined for each building type and each HVAC control through a two-step process: (1st) the optimal thickness of expanded polystyrene (EPS) insulation for the base architecture of the building (without any additional shading) was obtained; (2nd) the optimal length for external shades (considering the opaque elements insulated with the previously EPS thickness) was achieved. EPS thicknesses ranging from 0 cm (no insulation) up to 12 cm were checked, as this range aligns with economic viability for buildings in temperate Mediterranean climates [10,20]. Shade lengths within the range of 0 cm (no additional shading) to 150 cm were tested. For aesthetic reasons, the shade length was limited to 150 cm.

Due to the simplification adopted in the simulations (in steps of EPS thickness and of shade length), the optimal values of the thermal insulation thickness and of shade length can be slightly different from the values obtained. Also, they can even have a value greater than the maximum tested, respectively, 12 and 150 cm. Then, the values identified as "optimal" must be looked at as the "best solution" within the range of the values tested.

Based on a global analysis, it was discovered that the energy-optimal values for EPS thickness and external shade length differ depending on whether the HVAC system is controlled using PMV or T_{air} setpoints. However, these values are equal or nearly identical for control types A, B, and C, as well as for control types DT1, DT3, and DT5. Therefore, it suffices to specify whether the HVAC system control is based on PMV or T_{air} setpoints. The optimal values obtained for thermal insulation thickness and for shade length are summarized in Table 7, for the three types of Mediterranean climates (MC1, MC2, MC3) and the three climate change scenarios (NCC, MRS, HRS) considered, as a function of the type of HVAC system control.

The results presented in Table 7 indicate that the energy-optimal values for thermal insulation thickness and shade length tend to align with either the respective minimum values (0 cm, 0 cm) or the respective maximum values (12 cm, 150 cm, respectively) that were tested. Additionally, for assessment purposes, the buildings can be categorized as: (i) of permanent use (apartment, detached house, and clinic); (ii) of intermittent use and low internal thermal loads (school and bank branch); and (iii) of intermittent use and high internal thermal loads (supermarket).

In the case of buildings with permanent use, the energy-optimal thermal insulation thickness is consistently 12 cm across all types of HVAC system control, temperate Mediterranean climates, and climate change scenarios. This arises from the fact that, for these types of buildings (with low internal thermal loads) and passive constructive elements (with high thermal mass), the increase in thermal insulation thickness leads to a decrease in energy consumption for heating and an increase in energy consumption for cooling, as shown by the results of this study (figures not shown) and what is reported in the bibliography [10,20,30,42]. Additionally, with the increase in thermal insulation thickness, the rate of decrease in energy consumption for heating is greater than the rate of increase in consumption for cooling, which is reflected in a continuous decrease in energy consumption for air conditioning. In this type of buildings, the use of additional glazing shades is energetically advantageous when the HVAC system is controlled by PMV setpoints. On the other hand, these elements do not bring energy advantages when this control is performed by T_{air} setpoints.

Table 7. Energetically optimal values of thermal insulation (EPS) thickness (0 to 12 cm), and of external fixed horizontal shade length (Shd) (0 to 150 cm), as function of Mediterranean type of climate (MC1, MC2, MC3), type of control of HVAC system (PMV/T_{air}), and climate change scenario (NCC, MRS, HRS).

Apartment	**NCC: No Further Climatic Changes**						**MRS: Mid-Range Scenario (RCP 4.5)**						**HRS: High-Range Scenario (RCP 8.5)**					
Climate	**MC1**		**MC2**		**MC3**		**MC1**		**MC2**		**MC3**		**MC1**		**MC2**		**MC3**	
HVAC Control	**EPS [cm]**	**Shd [cm]**	**EPS [cm]**	**Shd [cm]**	**EPS [cm]**	**Shd [cm]**	**EPS [cm]**	**Shd [cm]**	**EPS [cm]**	**Shd [cm]**	**EPS [cm]**	**Shd [cm]**	**EPS [cm]**	**Shd [cm]**	**EPS [cm]**	**Shd [cm]**	**EPS [cm]**	**Shd [cm]**
PMV	12	80	12	60	12	40	12	110	12	90	12	60	12	150	12	130	12	110
T_{air}	12	0	12	0	12	0	12	0	12	0	12	0	12	0	12	0	12	0
Dwelling	**NCC: no further climatic changes**						**MRS: mid-range scenario (RCP 4.5)**						**HRS: high-range scenario (RCP 8.5)**					
Climate	**MC1**		**MC2**		**MC3**		**MC1**		**MC2**		**MC3**		**MC1**		**MC2**		**MC3**	
HVAC Control	**EPS [cm]**	**Shd [cm]**	**EPS [cm]**	**Shd [cm]**	**EPS [cm]**	**Shd [cm]**	**EPS [cm]**	**Shd [cm]**	**EPS [cm]**	**Shd [cm]**	**EPS [cm]**	**Shd [cm]**	**EPS [cm]**	**Shd [cm]**	**EPS [cm]**	**Shd [cm]**	**EPS [cm]**	**Shd [cm]**
PMV	12	100	12	70	12	50	12	140	12	110	12	90	12	150	12	130	12	110
T_{air}	12	0	12	0	12	0	12	0	12	0	12	0	12	0	12	0	12	0
Clinic	**NCC: no further climatic changes**						**MRS: mid-range scenario (RCP 4.5)**						**HRS: high-range scenario (RCP 8.5)**					
Climate	**MC1**		**MC2**		**MC3**		**MC1**		**MC2**		**MC3**		**MC1**		**MC2**		**MC3**	
HVAC Control	**EPS [cm]**	**Shd [cm]**	**EPS [cm]**	**Shd [cm]**	**EPS [cm]**	**Shd [cm]**	**EPS [cm]**	**Shd [cm]**	**EPS [cm]**	**Shd [cm]**	**EPS [cm]**	**Shd [cm]**	**EPS [cm]**	**Shd [cm]**	**EPS [cm]**	**Shd [cm]**	**EPS [cm]**	**Shd [cm]**
PMV	12	150	12	130	12	100	12	150	12	130	12	110	12	150	12	150	12	150
T_{air}	12	0	12	0	12	0	12	0	12	0	12	0	12	0	12	0	12	0
School	**NCC: no further climatic changes**						**MRS: mid-range scenario (RCP 4.5)**						**HRS: high-range scenario (RCP 8.5)**					
Climate	**MC1**		**MC2**		**MC3**		**MC1**		**MC2**		**MC3**		**MC1**		**MC2**		**MC3**	
HVAC Control	**EPS [cm]**	**Shd [cm]**	**EPS [cm]**	**Shd [cm]**	**EPS [cm]**	**Shd [cm]**	**EPS [cm]**	**Shd [cm]**	**EPS [cm]**	**Shd [cm]**	**EPS [cm]**	**Shd [cm]**	**EPS [cm]**	**Shd [cm]**	**EPS [cm]**	**Shd [cm]**	**EPS [cm]**	**Shd [cm]**
PMV	0	150	12	50	12	20	0	150	6	90	12	70	0	150	3	150	8	150
T_{air}	12	0	12	0	12	0	6	150	12	0	12	0	0	150	12	0	12	0
Bank	**NCC: no further climatic changes**						**MRS: mid-range scenario (RCP 4.5)**						**HRS: high-range scenario (RCP 8.5)**					
Climate	**MC1**		**MC2**		**MC3**		**MC1**		**MC2**		**MC3**		**MC1**		**MC2**		**MC3**	
HVAC Control	**EPS [cm]**	**Shd [cm]**	**EPS [cm]**	**Shd [cm]**	**EPS [cm]**	**Shd [cm]**	**EPS [cm]**	**Shd [cm]**	**EPS [cm]**	**Shd [cm]**	**EPS [cm]**	**Shd [cm]**	**EPS [cm]**	**Shd [cm]**	**EPS [cm]**	**Shd [cm]**	**EPS [cm]**	**Shd [cm]**
PMV	0	150	12	70	12	40	0	150	12	110	12	80	0	150	0	150	12	150
T_{air}	12	0	12	0	12	0	12	0	12	0	12	0	12	0	12	0	12	0
Super	**NCC: no further climatic changes**						**MRS: mid-range scenario (RCP 4.5)**						**HRS: high-range scenario (RCP 8.5)**					
Climate	**MC1**		**MC2**		**MC3**		**MC1**		**MC2**		**MC3**		**MC1**		**MC2**		**MC3**	
HVAC Control	**EPS [cm]**	**Shd [cm]**	**EPS [cm]**	**Shd [cm]**	**EPS [cm]**	**Shd [cm]**	**EPS [cm]**	**Shd [cm]**	**EPS [cm]**	**Shd [cm]**	**EPS [cm]**	**Shd [cm]**	**EPS [cm]**	**Shd [cm]**	**EPS [cm]**	**Shd [cm]**	**EPS [cm]**	**Shd [cm]**
PMV	0	150	0	150	0	150	0	150	0	150	0	150	0	150	0	150	0	150
T_{air}	0	150	12	150	12	150	0	150	12	150	12	150	0	150	12	150	12	150

In the case of the school and the bank branch, the values presented in Table 7 reveal that the energy-optimal thermal insulation thickness is greater when the HVAC system is controlled using T_{air} setpoints compared to PMV setpoints. As climate intensity increases (from MC1 to MC2 to MC3), the optimal insulation thickness tends to rise. Conversely, with more severe climate change scenarios (from NCC to MRS to HRS), the optimal thickness tends to decrease. When the Mediterranean climate is mild (MC1) and the HVAC system is controlled by PMV setpoints, the optimal solution is always the absence of thermal insulation (0 cm). Regardless of the climate type (MC1, MC2, or MC3), when T_{air} setpoints are used, the optimal EPS thickness is consistently 12 cm under the current climate scenario (NCC). Irrespective of the climate change scenario (NCC, MRS, or HRS), when the HVAC system is controlled by T_{air} setpoints, the optimal EPS thickness remains 12 cm in the case of moderate (MC2) and intense (MC3) Mediterranean climates. For these building types, additional glazing shades offer energy advantages when the HVAC system is controlled by *PMV* setpoints. However, these elements do not confer similar energy benefits when the HVAC system is controlled by T_{air} setpoints.

For the supermarket, the energy-optimal EPS thickness is 0 cm (i.e., no thermal insulation) when the control of the HVAC system is carried out by *PMV* setpoints and when the building is in a location with a mild Mediterranean climate (MC1). For all other situations, the optimal EPS thickness equals the maximum tested value of 12 cm. In this building, regardless of climate type or climate change scenario, the use of additional glazing shades is energetically advantageous when the HVAC system is controlled by both *PMV* and T_{air} setpoints.

Understanding the interplay between thermal insulation, glazing shading, climate characteristics, and HVAC control strategies is essential for energy-efficient design in buildings. Buildings' energy consumption is significantly influenced by the climatic conditions they face [7,10,12]. Thus, the severity of climate change will have a major influence on energy use for air conditioning. Consequently, optimizing building design in energy terms necessitates precise knowledge of the future climatic conditions [11–14]. Although achieving this precision is challenging, certain good practices can guide the process.

Within the tested climate change scenarios (NCC, MRS, and HRS) and the considered temperate Mediterranean climates (MC1, MC2, and MC3), as climate change severity increases, there is a tendency for reduced energy-optimal EPS thickness and for an increase in energy advantage of using glazing shades, but these trends are not highly significant. Then, buildings designed for good energy performance in the current climate (NCC) will maintain good performance in the future. Even if global warming reaches levels equivalent to the HRS scenario, well-designed buildings will remain energy-efficient. It should be recognized that good energy performance does not necessarily equate to optimal performance. Also, as local specific climate conditions play a significant role in buildings' energy demand, the extension of the previous statement to other climate types must be performed with caution, especially in hot and/or humid climates.

4.2. Energy Demands for Heating and for Cooling

Figure 2 illustrates the impact of climate change scenarios on annual energy demand for heating (left column) and for cooling (right column) across the six different building types incorporating the energy-optimal values for thermal insulation thickness and glazing shading length. Each case shown includes all types of setpoints (A, B, C, DT1, DT3, DT5) and temperate Mediterranean climates (MC1, MC2, MC3). As can be observed, the annual energy needs for heating and for cooling clearly depend on the building type of use, on the climate intensity (MC1, MC2, MC3) and on the climate change scenario (NCC, MRS, HRS).

In the published literature, it is commonly asserted that even in temperate climates, the demand for thermal energy for heating typically exceeds that for cooling. However, Figure 2 reveals that this statement does not universally hold true. Contrary to the general trend, the supermarket exhibits significantly higher energy needs for cooling than for heating in all climate change scenarios and climate types considered. Also, for all building types, cooling demands surpass heating demands in the HRS scenario (high-intensity climate changes), which emphasize the importance of addressing cooling requirements in future climate conditions. In the NCC (no further climatic changes) and MRS (medium-intensity climate changes) scenarios, heating demands exceed cooling demands for all buildings except the supermarket.

The supermarket experiences varying energy demands based on the season. Although winter requires minimal heating, summer necessitates substantial cooling efforts to maintain a comfortable environment for shoppers and staff. The low energy needs for heating are due to the high internal head loads and the occupants' high clothing insulation and activity level, whereas the substantial energy needs for cooling are due to the high internal head loads and the noticeable occupants' activity level. Otherwise, the thermal energy needs of the bank branch are both significant, for heating (in winter) due to occupants' sedentary activities and clothing thermal insulation below appropriate, and for cooling (in summer) mainly due to occupants' clothing thermal insulation above the recommended.

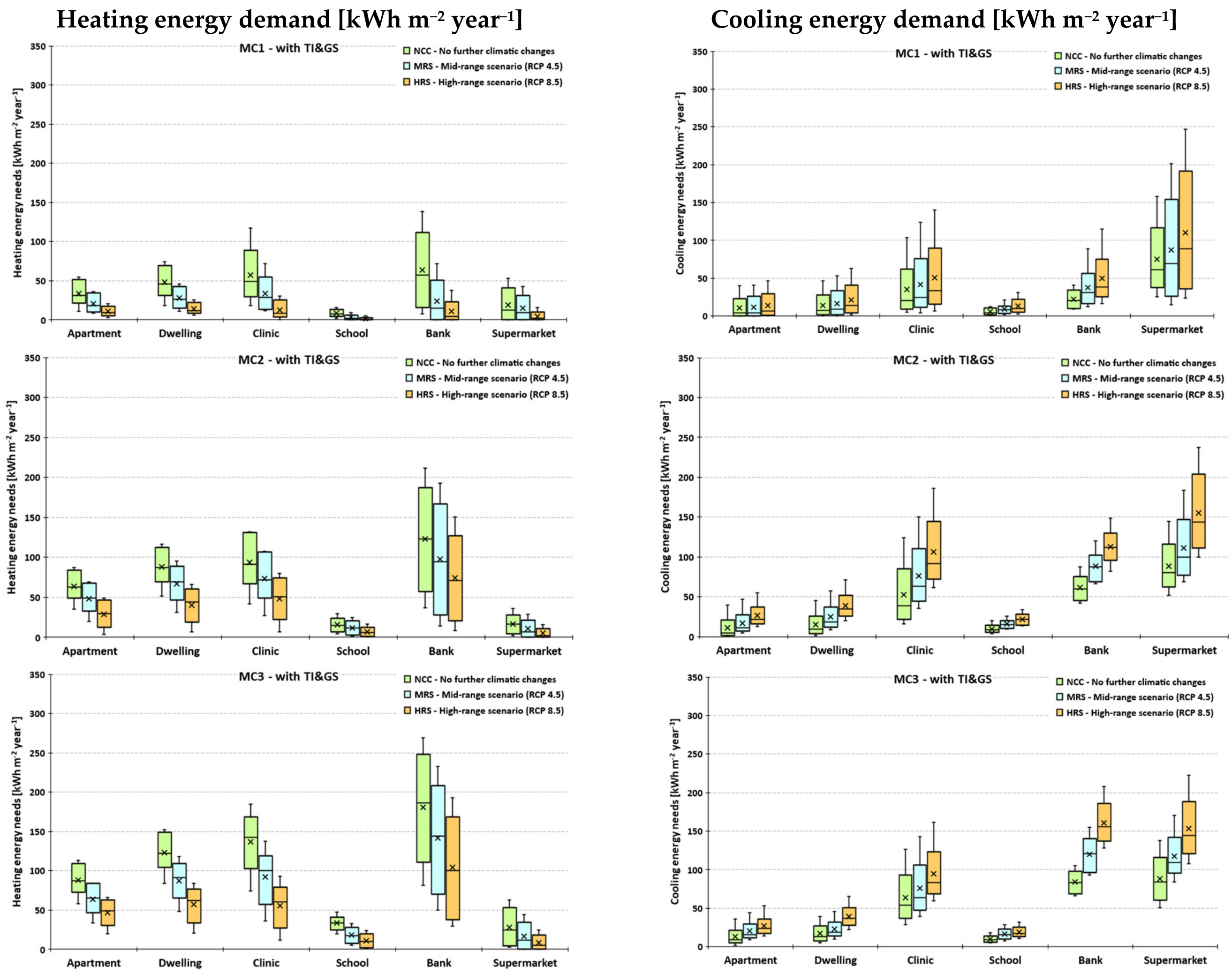

Figure 2. Buildings' annual energy demand for heating and for cooling for the three climate change scenarios and the three Mediterranean climate types (MC1, MC2, MC3) of buildings with the optimal values of thermal insulation thickness and glazing shading length (with TI&GS). Each case shown includes all setpoints (A, B, C, DT1, DT3, DT5).

Regardless of the climate change scenario, the buildings with the lowest energy demand for heating are the school (in the case of mild climate MC1) and the supermarket (in the cases of moderate MC2 and intense MC3 climates). The buildings with the highest energy demand for heating are the clinic (MC1 and MRS), the detached house (MC1 and HRS), and the bank branch (in all the other situations).

Irrespective of the climate type and across all climate change scenarios, the building with the lowest energy demand for cooling is the school. In climate types MC1 and MC2 and under all climate change scenarios, the supermarket experiences the highest energy requirements for cooling. In climate type MC3 and across all climate change scenarios, the building with the highest energy demands for cooling is the bank branch.

Regardless of the building type or the climate change scenario, thermal energy demands for climatization increase with the intensity of the climate (MC1 → MC2 → MC3). Irrespective of the building type or the climate intensity, the energy needs for heating decrease as the severity of climate change grows (NCC → MRS → HRS). Conversely, the energy needs for cooling rise as the severity of climate change increases. These two last statements align with extensive reports in the bibliography [12,26,27].

To assess the impact of climate change scenarios on energy demands for heating and cooling, the probability associated with a Student's *t*-test, considering a two-tailed distribution and two samples of unequal variance, was calculated using the NCC (present climate) scenario as the reference. The results obtained for the level of statistical difference, for scenarios mid-range (MRS) and high-range (HRS) and Mediterranean climates mild (MC1), moderate (MC2), and intense (MC3), are shown in Table 8.

Table 8. Student's *t*-test statistical significance of the difference relative to the NCC scenario of energy demands for heating and for cooling, for scenarios MRS and HRS and climate types MC1, MC2, and MC3. Legend: — → no statistical difference ($p > 0.05$), * → significant difference with $p < 0.05$, ** → significant difference with $p < 0.01$.

Building	Climate Type	Heating MRS	Demand HRS	Cooling MRS	Demand HRS
Apartment	MC1	—	*	—	—
	MC2	—	**	—	—
	MC3	—	**	—	—
Detached house	MC1	—	*	—	—
	MC2	—	**	—	*
	MC3	—	**	—	*
Clinic	MC1	—	*	—	—
	MC2	—	*	—	—
	MC3	—	**	—	—
School	MC1	—	*	—	—
	MC2	—	*	—	*
	MC3	—	**	—	*
Bank branch	MC1	—	—	—	—
	MC2	—	—	—	*
	MC3	—	—	—	**
Supermarket	MC1	—	—	—	—
	MC2	—	—	—	*
	MC3	—	—	—	*

The results shown in Table 8 reveal that, regardless of building and climate types, the difference relative to the present climate (NCC scenario) in energy demand for heating and for cooling is not statistically significant in the case of the mid-range scenario (MRS). Regardless of the type of climate, in the case of the climate change high-range scenario (HRS), the decrease in energy demand for heating is statistically significant for buildings with permanent use (apartment, detached house, and clinic) and the school, and not statistically significant for the bank branch and the supermarket. For the HRS scenario, the augmentation of energy demand for cooling is not statistically significant in the case of the mild climate (MC1), regardless of the type of building, and for the apartment and the clinic, regardless of the type of climate.

Figures 3 and 4 illustrate the annual energy demand for heating (left column) and cooling (right column) for buildings with permanent use (Figure 3) and for buildings with intermittent use (Figure 4), when placed in the moderate Mediterranean climate (MC2). Due to space limitations, only results related to climate MC2 were present, which fall between the mild (MC1) and intense (MC3) climates. The results shown in these figures demonstrate that the energy demands for heating and cooling indoor spaces depend on the building type of use, on the climate change scenario, on the type of operation of the climatization system, and on the existence of thermal insulation of opaque elements and glazing shading.

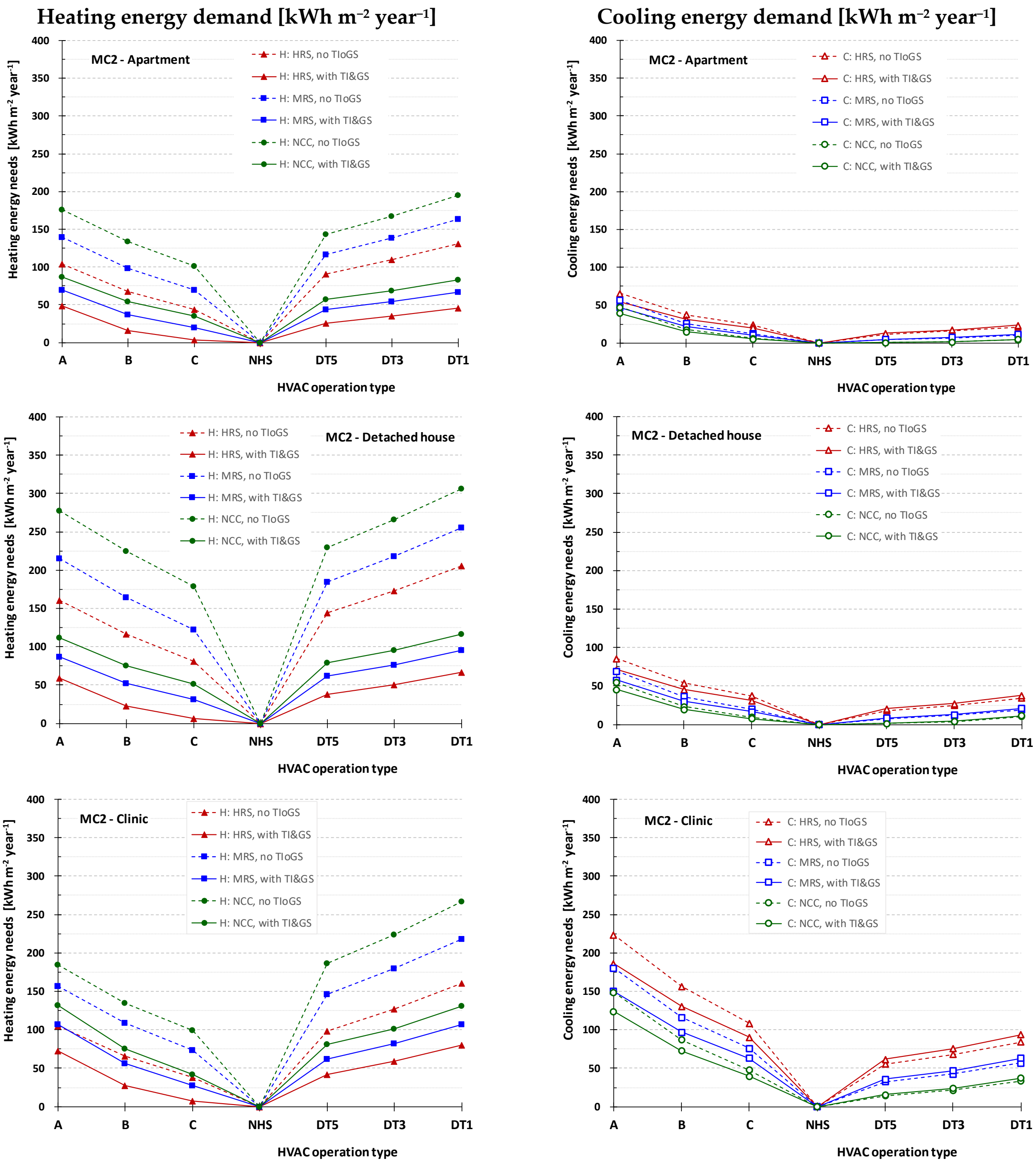

Figure 3. Annual energy demand for heating and for cooling of buildings with permanent use, in Mediterranean climate type 2 (MC2): NCC—no further climatic changes; MRS—mid-range scenario (RCP 4.5); HRS—high-range scenario (RCP 8.5); no TIoGS—without thermal insulation or glazing shading; with TI&GS—with energy-optimal thermal insulation and glazing shading.

In general, the results indicate that across all buildings and situations, the thermal energy requirements for heating are higher when the HVAC system control relies on indoor air temperature (T_{air}) setpoints compared to when it is based on predicted mean vote (*PMV*) setpoints. Conversely, for energy demands related to cooling, the situation is reversed; values are higher when the HVAC system control uses *PMV* setpoints rather than T_{air} setpoints. Therefore, from an energy demand perspective, the ideal HVAC control system operates based on *PMV* setpoints during the heating function and switches to T_{air} setpoints during cooling periods. However, in terms of thermal comfort, the energy-optimal HVAC control system consistently relies on *PMV* setpoints [7].

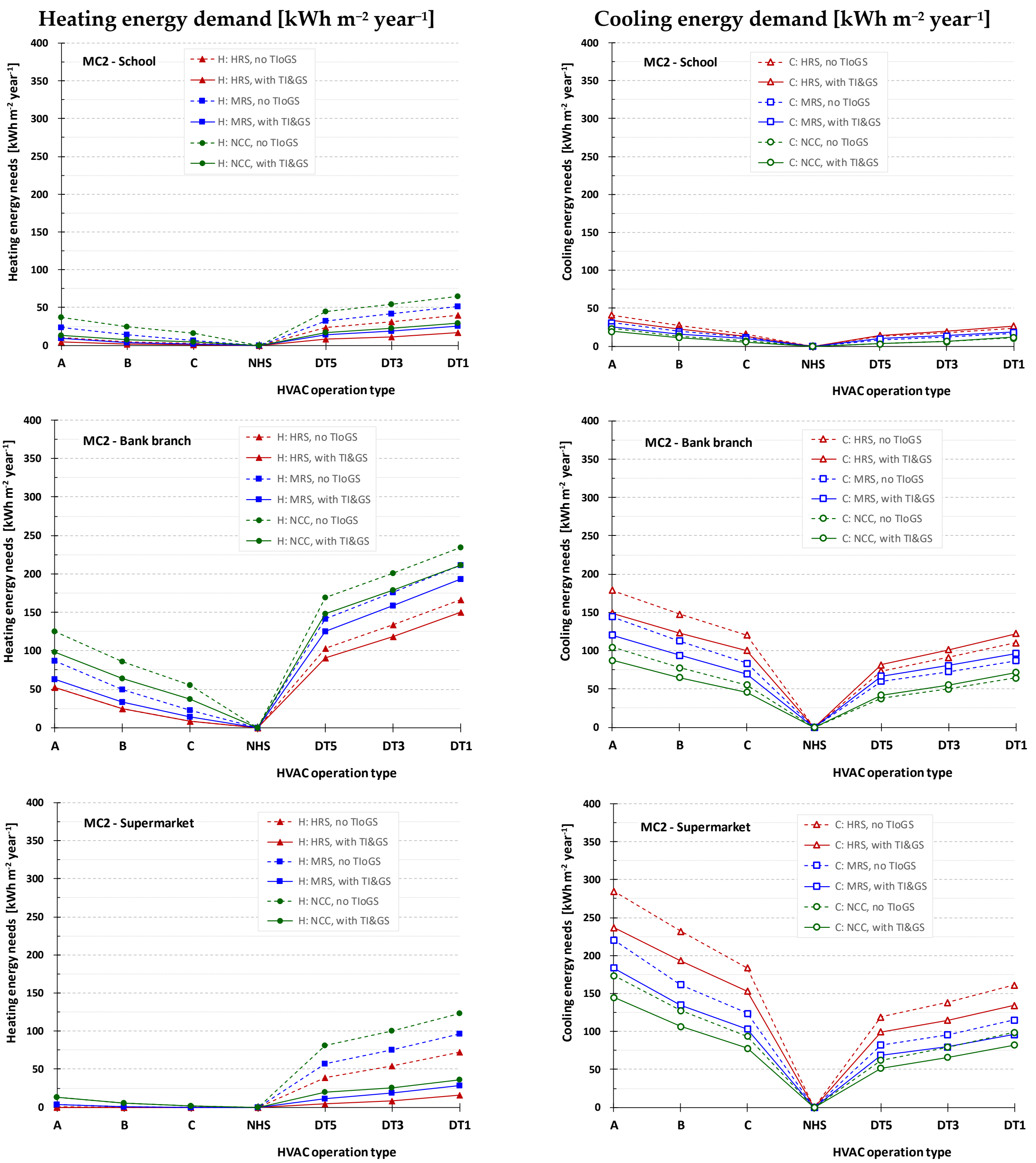

Figure 4. Annual energy demand for heating and for cooling of buildings with intermittent use, in Mediterranean climate type 2 (MC2): NCC—no further climatic changes; MRS—mid-range scenario (RCP 4.5); HRS—high-range scenario (RCP 8.5); no TIoGS—without thermal insulation or glazing shading; with TI&GS—with energy-optimal thermal insulation and glazing shading.

As stated in previous studies [7,10,20], increasing the thickness of thermal insulation applied to a building's opaque elements leads to improved thermal comfort indoors, to a substantial decrease in annual energy requirements for heating, and to a slight increase in those for cooling. Conversely, the installation of external glazing shades contributes to better thermal comfort (by eliminating excess indoor air temperature peaks) and reduces energy demands for cooling, albeit with an insignificant increase in heating requirements [34–37]. Thus, the energy impact of applying thermal insulation becomes evident through the graphs depicting heating demands (left column of Figures 3 and 4). Similarly, the significance of installing glazing shades is apparent from the graphs related to cooling needs (right column of Figures 3 and 4).

The results depicted in Figures 3 and 4 consistently demonstrate that, regardless of the climate change scenario, the application of thermal insulation to opaque elements of the building envelope consistently reduces energy demands for heating, which is particularly relevant for buildings with permanent use (apartment, detached house, and clinic) and has limited relevance for buildings that are intermittently occupied (school, bank branch, and supermarket). Conversely, when considering energy terms, the installation of exterior glazing shades is almost always beneficial, although it never becomes highly significant.

4.3. Energy Consumption by the HVAC System

The Heating, Ventilation, and Air Conditioning (HVAC) system in all buildings is based on a chiller/heat-pump of European class A+, with a seasonal coefficient of performance (*SCOP*) of 4.30 in heating mode, a seasonal energy efficiency ratio (*SEER*) of 5.85 in cooling mode, and on ventilation equipment with a performance coefficient of 70%.

The annual energy consumption by the HVAC system of the six buildings, when placed in the three Mediterranean climate types (mild (MC1), moderate (MC2), and intense (MC3)), exposed to the three climate change scenarios (no further climate change (NCC), mid-range (MRS), and high-range (HRS)), and considering energy-optimal values for thermal insulation thickness and glazing shading length, is depicted in Figure 5. The data are presented in the form of boxplot graphs, and each case including all setpoints (A, B, C, DT1, DT3, DT5).

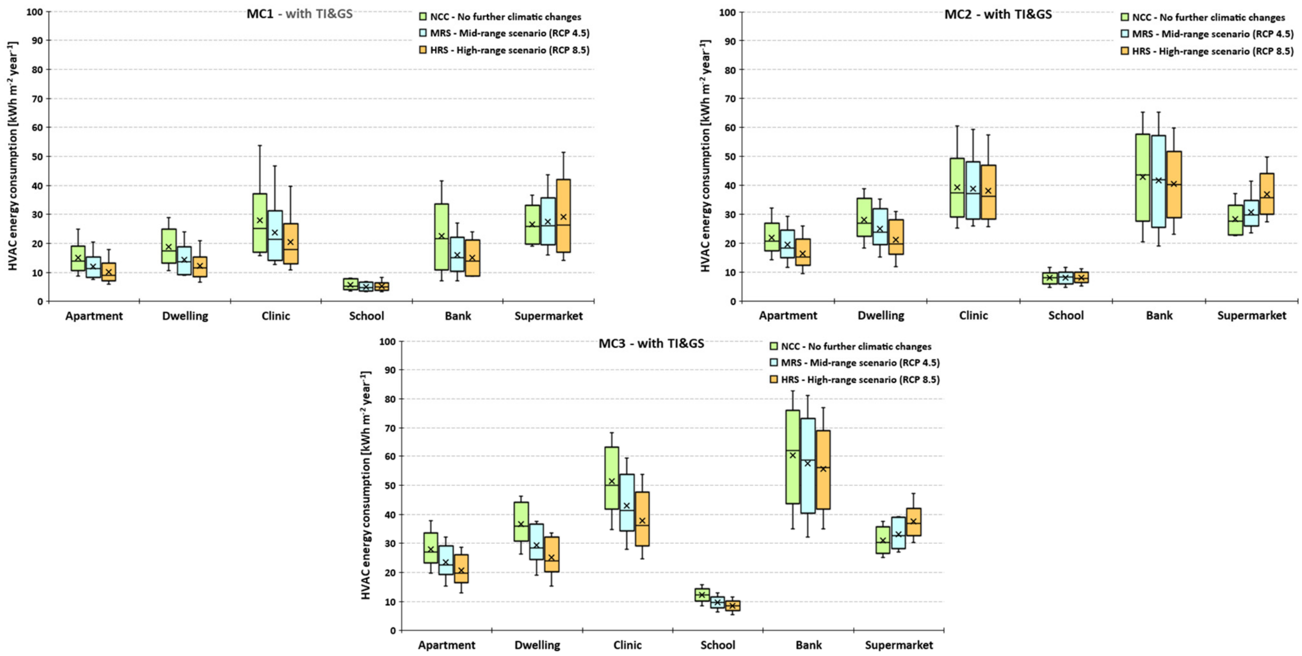

Figure 5. Annual energy consumption by the HVAC system (for heating, cooling, and ventilation) of buildings with the energy-optimal values of thermal insulation thickness and glazing shading length (with TI&GS), for Mediterranean climates mild (MC1), moderate (MC2), and intense (MC3). Each case shown includes all setpoints (A, B, C, DT1, DT3, DT5).

The results from Figure 5 underscore that, irrespective of climate type or climate change scenario, the school consistently exhibits significantly lower annual energy consumption for climatization compared to other buildings. In the mild climate (MC1), the clinic has the highest annual energy consumption for climatization under the present climate scenario (NCC). Meanwhile, the supermarket takes the lead in both the mid-range (MRS) and high-range (HRS) climate change scenarios. Regardless of the climate change scenario, the bank branch consistently demonstrates the highest annual energy consumption for climatization in temperate (MC2) and intense (MC3) climates.

Regardless of the climate change scenario, energy consumption for climatization in buildings generally increases with the intensity of the climate (MC1 → MC2 → MC3), except for the supermarket. Conversely, the supermarket's energy consumption decreases as the climate intensity rises. The reason behind this divergence lies in the supermarket's unique characteristics compared to other buildings. Specifically, the supermarket experiences higher internal heat gains (due to factors such as lighting, people, and devices), and occupants have higher clothing insulation and activity levels (as indicated in Table 4). Consequently, the supermarket's energy demand for cooling outweighs its heating requirements.

Irrespective of climate intensity, and except for the supermarket, the energy consumption for climatization in buildings decreases as the severity of climate changes increases (NCC → MRS → HRS). For the supermarket, this energy consumption rises with the increasing severity of climate change. The underlying reason is that, in this building type, the energy demand for cooling outweighs that for heating.

The results obtained with a Student's *t*-test for the level of statistical difference in the energy consumption by buildings' HVAC systems for scenarios mid-range (MRS) and high-range (HRS), and Mediterranean climates mild (MC1), moderate (MC2), and intense (MC3), are summarized in Table 9. These results reveal that, regardless of building and climate types, the difference in energy consumption for climatization relative to the NCC scenario is not statistically significant in the case of the mid-range scenario (MRS). In the case of the high-range scenario (HRS), whatever building type, the difference remains not statistically significant for buildings placed in the mild (MC1) and moderate (MC2) climates. Therefore, the difference becomes statistically significant only when both the intense climate (MC3) and the extreme climate change scenarios (HRS) coincide.

Table 9. Student's *t*-test statistical significance of the difference relative to the NCC scenario of energy consumption by the HVAC system, for scenarios MRS and HRS and climate types MC1, MC2, and MC3. Legend: — → no statistical difference ($p > 0.05$), * → significant difference with $p < 0.05$, ** → significant difference with $p < 0.01$.

Building	Climate Type	HVAC MRS	Consumption HRS
Apartment	MC1	—	—
	MC2	—	—
	MC3	—	*
Detached house	MC1	—	—
	MC2	—	—
	MC3	—	**
Clinic	MC1	—	—
	MC2	—	—
	MC3	—	*
School	MC1	—	—
	MC2	—	—
	MC3	—	*
Bank branch	MC1	—	—
	MC2	—	—
	MC3	—	*
Supermarket	MC1	—	—
	MC2	—	—
	MC3	—	*

Comparing the statistical differences related to energy consumption by the HVAC system (shown in Table 9) with those related to energy demands for heating and cooling (presented in Table 8), leads to the conclusion that the energy efficiency of the HVAC system plays a decisive role in determining the significance of the differences in energy consumption associated with various climate change scenarios. This fact highlights the critical importance of HVAC system energy performance in the energy consumption for climatization.

Figures 6 and 7 illustrate the annual energy consumption for heating, cooling, and ventilation in buildings with permanent use (Figure 6) and in buildings with intermittent use (Figure 7), when placed in the Mediterranean climates MC1 (mild; left column) and MC3 (intense; right column). As shown, the energy consumption by the HVAC system depends on the building type of use, the existence of thermal insulation of opaque elements of the building's envelope and of external glazing shading, the type of control of climatization system operation, the climate change scenario, and the Mediterranean climate type.

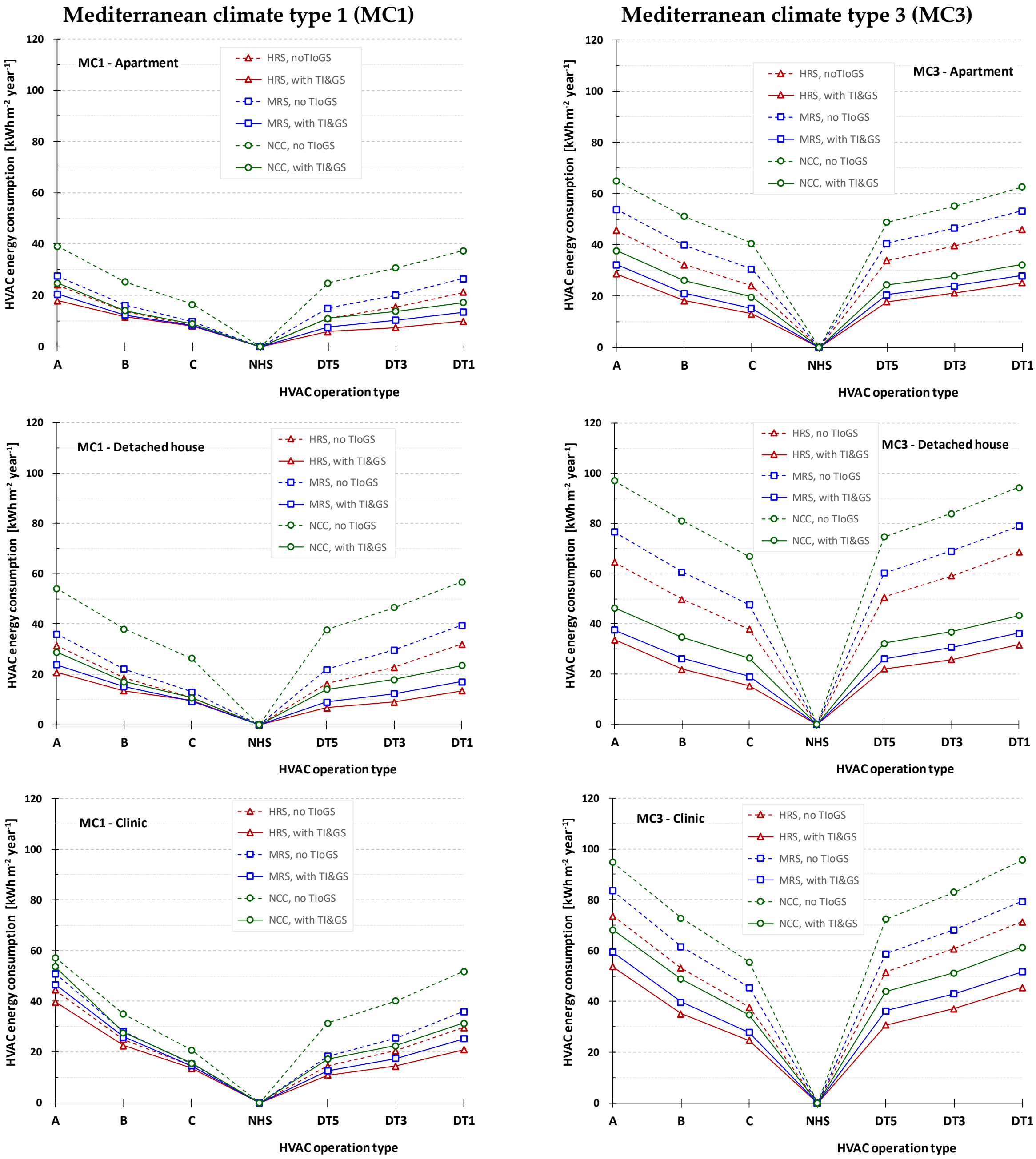

Figure 6. Annual energy consumption by the HVAC system (for heating, cooling, and ventilation), in Mediterranean climates type 1 and 3, of buildings with permanent use. Legend: NCC—no further climatic changes; MRS—mid-range scenario (RCP 4.5); HRS—high-range scenario (RCP 8.5); no TIoGS—without thermal insulation or glazing shading; with TI&GS—with energy-optimal thermal insulation and glazing shading.

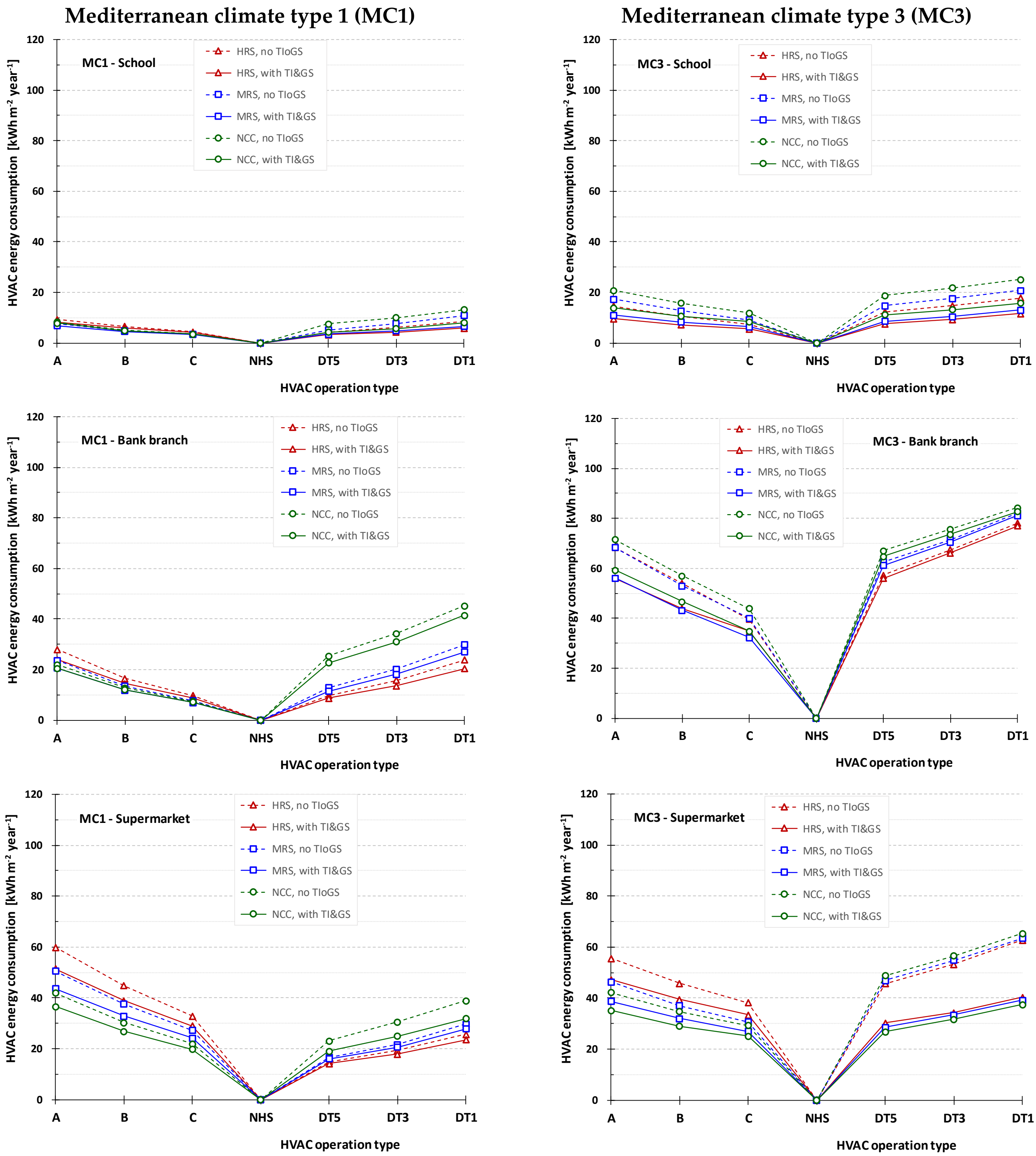

Figure 7. Annual energy consumption by the HVAC system (for heating, cooling, and ventilation), in Mediterranean climates type 1 and 3, of buildings with intermittent use. Legend: NCC—no further climatic changes; MRS—mid-range scenario (RCP 4.5); HRS—high-range scenario (RCP 8.5); no TIoGS—without thermal insulation or glazing shading; with TI&GS—with energy-optimal thermal insulation and glazing shading.

In general, the results highlight that the influence of climate type and the presence of thermal insulation in opaque elements and external glazing shades is much more pronounced for buildings with permanent use (apartment, detached house, and clinic) than for buildings with intermittent use (school, bank branch, and supermarket).

The benefits of having thermal insulation in opaque elements and external glazing shades become more pronounced as the climate intensity increases (MC1 → MC2 → MC3). Interestingly, these benefits remain consistent across all climate change scenarios (NCC, MRS, HRS). These statements emphasize the importance of energy-efficient building design regardless of the specific climate change context.

As mentioned earlier, the type of control of the climatization system operation is directly linked to the desired thermal comfort. The results depicted in Figures 6 and 7 reveal that, as expected, energy consumption by the air conditioning system increases as the quality of thermal comfort improves (from C → B → A; and from DT5 → DT3 → DT1). This increase is more pronounced in buildings with permanent use than in those with intermittent occupancy.

4.4. Influence of HVAC System Type of Control

Different types of HVAC system control led to different levels of thermal comfort indoors. The relation between the type of setpoint and the thermal comfort level is not addressed here, but it was analyzed in another work of the authors [7], where the same buildings and locations were considered, but for the present climate (NCC scenario).

In this study, six control types were considered (as detailed in Table 5), three of them by the traditional setpoints of indoor air temperature (T_{air})—referred as DT1, DT3, and DT5—and the remaining three by setpoints of the predicted mean vote (*PMV*)—designed as A, B, and C. In terms of thermal comfort quality, controls A and DT1 guarantee a high level, B and DT3 a good level, and C and DT5 a moderate level. These traits highlight the importance of selecting the appropriate control strategy to ensure the desired occupants' thermal comfort.

A comprehensive comparison was conducted to explore the relationship between the two control types of air conditioning system operation (*PMV* or T_{air} setpoints), the three Mediterranean climate types (MC1, MC2, MC3), and the three climate change scenarios (NCC, MRS, HRS), considering the buildings with the energy-optimal values of thermal insulation thickness and of glazing shading length. Table 10 summarizes the findings of this assessment, where the type of HVAC system control associated with lower annual energy consumption for air conditioning is identified.

As mentioned earlier, across all buildings and situations, the energy consumption by the air conditioning system increases as the quality of thermal comfort improves (from C → B → A; and from DT5 → DT3 → DT1), but this increase is more pronounced in buildings with permanent use than in those with intermittent occupancy. Additionally, the thermal energy requirements for heating are lower when the HVAC system control relies on *PMV* setpoints, whereas the energy demands for cooling are lower when the control is based on T_{air} setpoints. This inference emphasizes the trade-off between thermal comfort, type of control of HVAC system operation and energy consumption for climatization that must be considered in building design.

The results presented in Table 10 reveal that the energy-optimal type of HVAC system control depends on the building and on the Mediterranean climate types. Interestingly, it is independent of the climate change scenario. In the case of intense climate (MC3), regardless of the building type, controlling the HVAC system using *PMV* setpoints consistently leads to lower energy consumption for climatization. In the case of climate types MC1 (mild) and MC2 (moderate) and for buildings with permanent use (apartment, detached house, and clinics) and the supermarket, it is preferable to control the HVAC system using T_{air} setpoints. For the school and the bank branch, the better option is always to control the HVAC system using *PMV* setpoints.

Previous insights emphasize the importance of tailored HVAC control strategies based on specific building contexts and present climate conditions. Conversely, within temperate Mediterranean climates, the severity of climate change is unlikely to significantly affect the better control type of HVAC systems operation.

Table 10. HVAC system control type that leads to lower energy consumption for climatization, for the three Mediterranean climate types (MC1, MC2, MC3) and the three climate change scenarios (NCC, MRS, HRS), considering the buildings with the energy-optimal values of thermal insulation thickness and of glazing shading length.

Building	Climate Type	Climate NCC	Change MRS	Scenario HRS
Apartment	MC1	T_{air}	T_{air}	T_{air}
	MC2	T_{air}	T_{air}	T_{air}
	MC3	PMV	PMV	PMV
Detached House	MC1	T_{air}	T_{air}	T_{air}
	MC2	T_{air}	T_{air}	T_{air}
	MC3	PMV	PMV	PMV
Clinic	MC1	T_{air}	T_{air}	T_{air}
	MC2	T_{air}	T_{air}	T_{air}
	MC3	PMV	PMV	PMV
School	MC1	PMV	PMV	PMV
	MC2	PMV	PMV	PMV
	MC3	PMV	PMV	PMV
Bank Branch	MC1	PMV	PMV	PMV
	MC2	PMV	PMV	PMV
	MC3	PMV	PMV	PMV
Supermarket	MC1	T_{air}	T_{air}	T_{air}
	MC2	T_{air}	T_{air}	T_{air}
	MC3	PMV	PMV	PMV

5. Conclusions

This study aims to systematically assess how climate changes, properties of construction elements, and the type of control used in HVAC systems impact the energy requirements of six buildings (apartment, detached house, clinic, school, bank branch, and supermarket) situated in a temperate Mediterranean climate.

The buildings were situated in three different climate zones: mild (MC1), moderate (MC2), and intense (MC3). The buildings' envelopes incorporate a traditional External Thermal Insulation Composite System (ETICS) based on expanded polystyrene (EPS). Insulation thicknesses ranging from 0 (without insulation) to 12 cm, as well as horizontal external fixed shades with lengths varying from 0 (absence) to 150 cm, were tested. Six different setpoint ranges for the HVAC system control were evaluated: three based on the predicted mean vote (PMV) and three based on the indoor air temperature (T_{air}). For the year 2070, three climatic change circumstances were assumed: (i) maintaining the current climate (NCC); (ii) resulting from medium-intensity climate changes (mid-range scenario, MRS); and (iii) subsequent from extreme climate changes (high-range scenario, HRS).

Climate hourly dataset files were prepared by applying "coefficients" predicted by "global climatic models" to present-day climate data using the "morphing procedure" methodology. A Student's t-test was performed on air temperature (T_{air}), relative humidity (RH), and horizontal global solar radiation ($HGSR$). In relation to present climate (scenario NCC), the other two (MRS and HRS) exhibit a statistically significant difference ($p < 0.001$) for the parameters T_{air}, RH, and $HGSR$ across the three climate types (MC1, MC2, and MC3). Additionally, there is a statistically significant difference ($p < 0.001$) between the MRS and HRS scenarios for T_{air} and RH, but not for $HGSR$ ($p > 0.05$).

The energy-optimal values for thermal insulation thickness and the length of the shade tend to align with either the respective minimum (0 cm, 0 cm) or maximum values (12 cm, 150 cm, respectively) that were tested. Generally, this optimal insulation thickness is greater when the HVAC system is controlled using T_{air} setpoints compared to PMV setpoints. This thickness tends to increase with higher climate intensity and decrease with more severe climate change. Except for the supermarket, the use of additional glazing shades is energetically advantageous when the HVAC system is controlled by *PMV* setpoints, but not when it is performed by T_{air} setpoints. For the supermarket, the use of additional glazing shades is advantageous regardless of the HVAC control type.

As expected, irrespective of building and climate types, an escalation in the severity of climate changes reduces the energy requirements for heating and amplifies the energy demands for cooling. The relative magnitude of these fluctuations depends on both the specific building and the climate type.

When comparing the two types of HVAC system control, the thermal energy requirements for heating are lower when the control of the HVAC system is performed by *PMV* setpoints, and the energy demands for cooling are lower when this control is performed by T_{air} setpoints. Therefore, from an energy demand perspective, the ideal HVAC control system operates based on *PMV* setpoints during heating periods and switches to T_{air} setpoints during cooling periods.

As anticipated, energy consumption by the air conditioning system increases with improved thermal comfort, more pronounced in buildings with continuous occupancy than in those with intermittent use. Regarding energy consumption for climatization, the optimal type of HVAC system control varies based on the specific building and climate conditions, but not of the climate change scenario.

In all building types and climates, relative to the current climate (NCC scenario), the difference in energy demands for heating and cooling is statistically significant only in the case of extreme climate change (HRS). On the other hand, the energy efficiency of the HVAC system is also a determining factor in its energy consumption. Therefore, the statistical significance of the difference between energy needs cannot be directly extrapolated to energy consumption for air conditioning. If buildings are equipped with an HVAC system based on a class A+ chiller/heat-pump, compared to the NCC scenario, the difference in energy consumption for climatization is only statistically significant when the HRS scenario and climate type MC3 are simultaneously present.

For buildings equipped with an HVAC system based on a class A+ or higher chiller/heat-pump, the impact on energy consumption for air conditioning due to factors such as thermal insulation, external glazing shading systems and HVAC system control type depends very little on the climate change scenario. Consequently, a building designed for good energy performance in the current climate will likely maintain that efficiency when exposed to the climate resulting from future climate change. As the energy efficiency of the HVAC system plays a crucial role, so this assertion may not hold if the energy efficiency of the air conditioning system is significantly lower than the one considered in this study.

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