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Integrated Analysis of Energy Saving and Thermal Comfort of Retrofits in Social Housing under Climate Change Influence in Uruguay

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Received: 1 May 2020; Accepted: 31 May 2020; Published: 5 June 2020

Abstract: Energy improvement studies normally use energy demand reduction as an indicator, disregarding dwellings that do not use air-conditioning systems or do so only under extreme weather conditions. They also do not quantify the impact of climate change on results. This research seeks to evaluate and prioritize energy improvements for existing Uruguayan dwellings, assessing energy demand and thermal comfort in both the current and future climate. A social dwelling was monitored and calibrated to assess energy efficiency measures simulating the current climate and for 2050 (IPCC Scenario A2). The results show that improvements must be linked to the use of air-conditioning in dwellings. When air-conditioning use is unknown, for example, in public policy, thermal transmittance in walls should be between 0.50–0.61 W/m^2 K, in roofs between 0.32–0.47 W/m^2 K, in openings 2.7 W/m^2 K, airtightness under 5 ACH n50 and with solar protections. However, when the use under free running is certain, thermal transmittance in walls and roofs should be 0.85 W/m^2 K with an airtightness of 9.2 ACH n50 and solar protection used to avoid overheating. The operational ventilation and solar protection parameters were helpful to guarantee comfort, underlining the need for their inclusion and to train those who use them.

Keywords: dwelling retrofit; adaptive comfort; thermal performance; energy performance; social housing; climate change

1. Introduction

Nowadays, the minimization of energy consumption (EC), eradication of fuel poverty (FP) and mitigation of climate change (CC) are the main challenges of the building sector [1]. Buildings consume between 30% and 40% of the world's energy [2], and according to the Internal Energy Agency, this could rise to 38.4 PWh by 2040 [3]. Currently, the exhaustion of non-renewable resources, along with global warming, is demanding more efficient buildings and the use of renewable energy [1]. Economic slowdown and CC have forced politicians and scientists to rationalize energy use around the world [4,5]. For this reason, energy consumption in buildings and consumption per capita are no longer indicators of economic prosperity and social welfare [6].

The consumption of a building is associated to multiple factors, with the demands for indoor comfort of the users, the energy efficiency (EE) of the envelope and the air-conditioning systems, standing out [7]. An unsuitable indoor temperature or deficient EE can lead to users being uncomfortable or that EC is high. Therefore, the sustainability level of the construction can be greatly affected by said parameters in order to achieve a low EC [8].

In addition, the use of active conditioning systems is a matter of discussion, due to the need for more resources to satisfy energy demands in a scenario where FP and energy prices increase [9–11]. For this reason, many current studies in the field of climate adaptation in the residential sector focus on the study of comfort, trying to reduce the use of active measures, while intensifying passive strategies [12]. On the other hand, the buildings must guarantee inhabitability and EE conditions to face CC projections [13]. In summary, in order to face CC conditions, buildings should focus on maintaining healthy conditions and indoor comfort without an excessive use of energy.

CC mitigation measures have been embodied in international building regulations and standards through passive envelope strategies and passive thermal conditioning techniques, seeking in this way, to reduce energy needs for air-conditioning, improving the EE of active systems and incorporating renewable energies, while contributing towards reducing CO_2 emissions [14]. In new buildings, it is possible to apply multiple strategies to obtain the desired performance (construction solution, layout, morphological and spatial setup). In existing buildings, this starts from certain conditioning factors like the shape, orientation, vernacular buildings, technological mismatch, regulatory problems, relationship with the surroundings and materiality. These are related to the construction practices, standards and regulations that existed when they were built [15]. Therefore, the age of buildings determines their thermal and energy performance.

Andrić, Koc and Al-Ghamdi established a classification of energy retrofitting measures in housing, identifying conventional (passive, active) and additional measures (See Table 1) [16]. Passive measures are ones that mainly focus on energy flows between the indoor and outdoor space through the envelope, either naturally or intentionally. Active measures focus on energy production, control, lighting and Heating, Ventilating and Air Conditioning systems (HVAC). There is a third category called "additional measures" that involves the thermal mass, the windows-to-wall ratio and setpoint temperatures [16]. Redistribution and changes to the volume of the indoor space can also be added to these.

A subcategory that can be identified, along the lines of what Van Hooff et al. and Escandón et al. presented, is one that is associated to the "operational parameters", mobile solar devices, natural ventilation and night cooling [17,18]. Other research explores the combination of passive and active strategies, like natural ventilation used together with orbit fans to improve comfort conditions through the increase of air velocity [19] In addition, others such as LED lighting systems or the installation of self-producing energy systems for the target of near-zero energy performance could be included [20,21].

The effectiveness of these measures is determined by the intensity of use and both the current and future thermal comfort demands [22]. The measures generally focus on reducing the demand, but also generate positive impacts on living conditions, especially where there are economic difficulties in accessing energy [23]. For this reason, the use of the energy demand or consumption as an indicator to quantify the performance of dwellings is under discussion, and more concretely for those that do not use air-conditioning systems or solely do so under extreme weather conditions [7]. Consequently, some authors have identified that the percentage of time where free-running dwellings can work within comfort ranges using adaptive comfort models is a more accurate indicator in these cases [13,24]. Adaptive comfort models are based on the natural tendency of individuals to adapt their thermoregulation, clothing and psychological conditions to the changing outdoor climate conditions under natural ventilation conditions [25]. In this way, several studies have tried to find the equation for predicting the thermal sensation based on multiple factors like the type of climate [26], socioeconomic level [24], age of people [19], among others. Unlike other comfort standards, this allows for a larger range of temperatures linked to the outdoor temperatures of previous days.

This aspect garners relevance in the context of Uruguay, where it is seen that part of the residential sector does not meet the thermal comfort requirements of its occupants [27], as most dwellings were built before thermal regulations came into force [28]. This has a direct repercussion on the air-conditioning energy demand and on the possibility of the user to face the economic cost of maintaining suitable comfort conditions [29]. Despite this, energy consumption in the residential sector represents 18% of the energy demand of the country with a sustained upward trend [30]. In addition, just like in other areas of Latin America, contaminating energies are used to improve thermal conditions during cold periods, compromising the occupants' health and producing important contamination issues [31]. According to the Continuous Survey of Homes from 2013 [17,18], 54% of homes use a wood burner and 42% a gas heater for heating, while only 24% use electricity [32]. On the other hand, the energy regulations are relatively new and are solely meant for new homes, with lower requirement levels versus regulations in similar climates [33,34].

Table 1. Classification of energy retrofitting measures of dwellings. Source: Adapted from Andrić, Koc and Al-Ghamdi [16].

Category			Description
Conventional measures	Passive measures	Constructive parameters	Additional insulation Improved air-tightness of the envelope Energy efficient glazing Solar shading fixed devices/overhangs Green roofs/walls Solar reflectivity/absorptivity
		Operation parameters	Natural ventilation/night cooling Solar shading mobile devices
	Active measures		Solar panels (PV panels and solar collectors) Heat pumps Connection to district heating/cooling Energy efficient lighting Energy efficient appliances Sophisticated control devices
Additional measures			Thermal mass Windows-to-wall ratio Indoor comfort temperatures Redistribution of space usages Modification of interior volume

On the other hand, studies on the energy performance of buildings are usually run using historic climate data, producing solutions that struggle to adapt to the intensity of the CC that the building is going to face during its lifespan [35]. This has led to many research projects being run around the world in recent years that include climate projections. However, those applied to buildings in the national context are limited [1,16,36,37].

The goal of this research is to assess and prioritize energy improvement measures for existing Uruguayan homes based on their current and future thermal and energy performance, integrating the energy demand and time in comfort as indicators, using adaptive thermal comfort models and climate change scenarios (IPCC A2 Scenario).

This paper is organized into the following sections: First, Section 2 describes the materials and methods used in the research, presenting the choice and calibration of the case study, the methodology applied to generate current and future climate files, as well as the indicators used to assess the improvements. Section 3 analyzes the results obtained by applying the energy improvement measures on the base case, assessing their energy and thermal performance individually and comparatively, considering the usage of the dwelling between 2020–2050. Finally, Section 4 presents the main conclusions of the study.

2. Materials and Methods

2.1. Social Housing in Uruguay

In Uruguay, Montevideo is home to 38% of the country's dwellings and almost 40% of its inhabitants [38]. From these, 53% are single-family households, 10% are collective one-floor dwellings and 32% are apartment blocks. Therefore, 63% are typologies that have a large exposed envelope surface and a higher thermal exchange [39]. A total of 87% of the Montevideo dwellings are over 10 years old and were built before the incorporation of EE requirements in the regulations [40]. In addition, 90.6% of the Montevideo dwellings have brick or concrete block walls with an outer finish, 87% have finished "tile, wood, etc." floors and 79.5% of the roofs are built with "concrete slabs or overhangs". In terms of surface area, 32% of Montevideo dwellings have a surface area of between 41 and 60 m^2, and 36% have a surface area of between 61 and 100 m^2 [38].

The energy simulation results are closely tied to the specific models being considered and, for this reason, must be chosen so that they are representative and extract results that can be widely used. As a result, it is necessary to characterize them based on the location, typology, age, geometry, area, number of floors, exposed surface, materiality and transmittance of the envelope to ensure representativity [41,42]. Thus, the dwelling chosen for the study is a detached single-family home with a surface area of 70.4 m^2, belonging to the social housing program [43]. The building systems and their characteristics can be seen in Table 2. It has three bedrooms, a living room, a kitchen and a bathroom (See Figure 1).

Table 2. Material and thermal characteristics of the envelope.

Component	**Layers**	**Thickness (m)**	**U-Value (w/m^2 k)**	**Cp [1] (kj/m^2k)**
Exterior wall	Interior cement plaster Hollow concrete wall Exterior cement plaster	0.18	2.62	186.2
Roof	Interior cement plaster Reinforced concrete slab cast in place Lightweight concrete Cementitious screed Aluminum bitumen membrane	0.165	3.42	225.0
Floor	Ceramic Tile Cement mortar Concrete cast in place	0.12	2.60	150.2
Interior wall	Interior cement plaster Hollow concrete wall Exterior cement plaster	0.15	2.22	186.3

Component	Type	Opening (%)	Frame	Glass	U (w/m^2 k)	Ts [2]	Tv [3]	Solar protection
Window (W1)	Casement	100%	Metal	Single 4 mm	5.87	0.81	0.89	none
Window (W2)	Pivot	100%	Metal		5.87	0.81	0.89	none
Door (D1)	-	100%	Wood		2.82	-	-	-
Door (D2)		100%	Metal/glass		5.89	0.81	0.89	-

Note: [1] Cp—Internal Heat Capacity; [2] Ts: Solar Transmittance; [3] Tv: Visible transmittance.

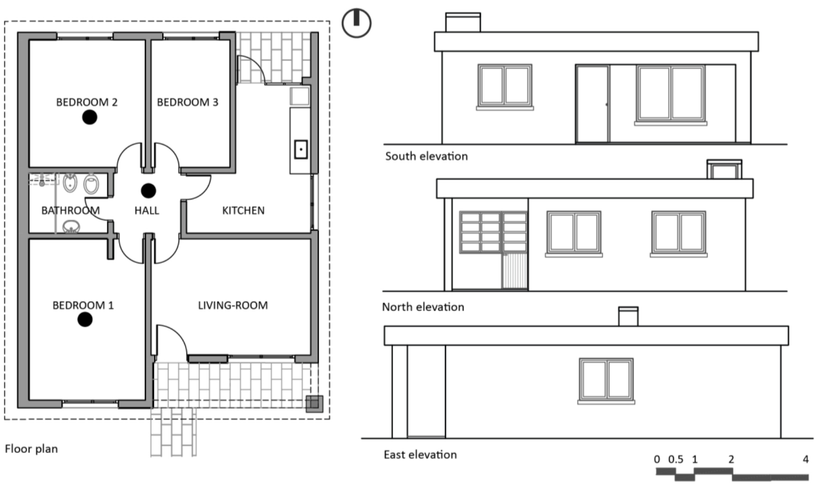

Figure 1. Model of the floor plan and facades and indication of the monitored rooms.

The operation and use conditions were established based on the average size of homes of the lowest quintiles, determining an occupation of four people [44], and loads and occupational and use schedules, following Picción et al. [45,46]. In addition, a ventilation flow of 2.5 lt/s/person and 0.3 l/s/m^2 was set [47]. A detached dwelling was studied with a larger exposed and unobstructed surface area, assumed as being the most unfavorable situation [48]. The main south-facing facade was considered for the case study.

2.2. Generation of Weather Data for the Calibration and Analysis of EE Improvements

The city of Montevideo (34°50′ S, 56°12′ W, 16.27 masl), according to the Koppen climate rating, has a "Cfa", template, moderate and rainy climate with template winters and humid and hot summers, with rain throughout the year. It is characterized by a significant thermal range, both in the seasonal period (12.1 °C between January and July), and in the daily thermal range (between 7.8 °C in July and 10.4 °C in January).

In the research, three types of weather files were used for the location. The first (Climate for calibration) was prepared with the weather data (dry bulb temperature, wet bulb temperature and humidity) obtained from the National Meteorology Institute (INUMET) from the El Prado weather station, located in a neighborhood of the city [49] and with horizontal global radiation data obtained from the meteorology station located in the Engineering Faculty building at the University of the Republic in Montevideo [50]. This information was included in an .epw file using Elements© program (v 1.0.6, Big Ladder Software LLC, Denver, CO, USA) [51].

The second (current climate) and third type (future climate) of climate files were used to assess EE improvement measures. The standard meteorological file of the current climate (TMY) and the future climate file for the A2 scenario projected for 2050, were obtained from Meteonorm© (v 7.0, Meteotest AG, Bern, Switzerland), indicating the corresponding coordinates of the site studied [52]. For future scenarios, the program uses the Hadley CM3 weather model for IPCC AR4 scenarios, then a downscaling process to a local scale takes place to obtain the hourly weather files. The A2 scenario for 2050 was chosen on being a period that is in line with the lifespan for energy improvements of existing dwellings [14]. It is important to consider that the files obtained represent projections of standard meteorological years with a limited representativity of localized weather variations of extreme climate change associated phenomena [53].

2.3. Monitoring and Calibration of the Model

The monitoring was done between the 13th and 31st of May 2019, obtaining hourly air temperature and humidity data using a HOBO-ONSET UX100-003 model recorder. Three rooms in the dwelling were monitored, Bedroom 1, Bedroom 2 and the Living Room, aiming at covering spaces with different uses and orientations (See Figure 1). The dwelling, during the measurement period, operated under free running, except for short, one-off periods where a gas heater was used in bedroom 1. These were recorded by the occupants and discarded for the calibration.

The physical and usage conditions obtained through a physical survey of the dwelling were considered to prepare the model (see Table 2). The loads and calendars of use and ventilation for the calibration were prepared following the statement of use of its occupants (See Figure 2).

A model was built in the DesignBuilder© program (v 6.1.4.007, DesignBuilder Software Ltd, Stroud, UK) using the information collected, calibrated following the standards of Ashrae Guideline 14 [54]. It considered that the Mean Bias Error (MBE) between the simulation and monitoring temperatures must be between 10% and −10% and the Square Root Coefficient Variation of the Mean Bias Error (CV(RMSE)), lower than 30%.

Once the materiality was configured, usage parameters and outdoor weather conditions like the airtightness level and soil temperatures, parameters that could not be measured onsite, were used to calibrate the model. These variables were adjusted until they reached Ashrae Guideline 14 standards. For airtightness, the ranges determined for masonry-based dwellings in other research projects were considered [55]. For ground temperature, the model was validated using the ground domain tool in DesignBuilder, bearing in mind a conductivity of 1.5 W/m K, a specific weight of 2085 J/kg G, a density of 1500 kg/m^3, a ground domain depth of 10 m and an incidence perimeter of 6 m.

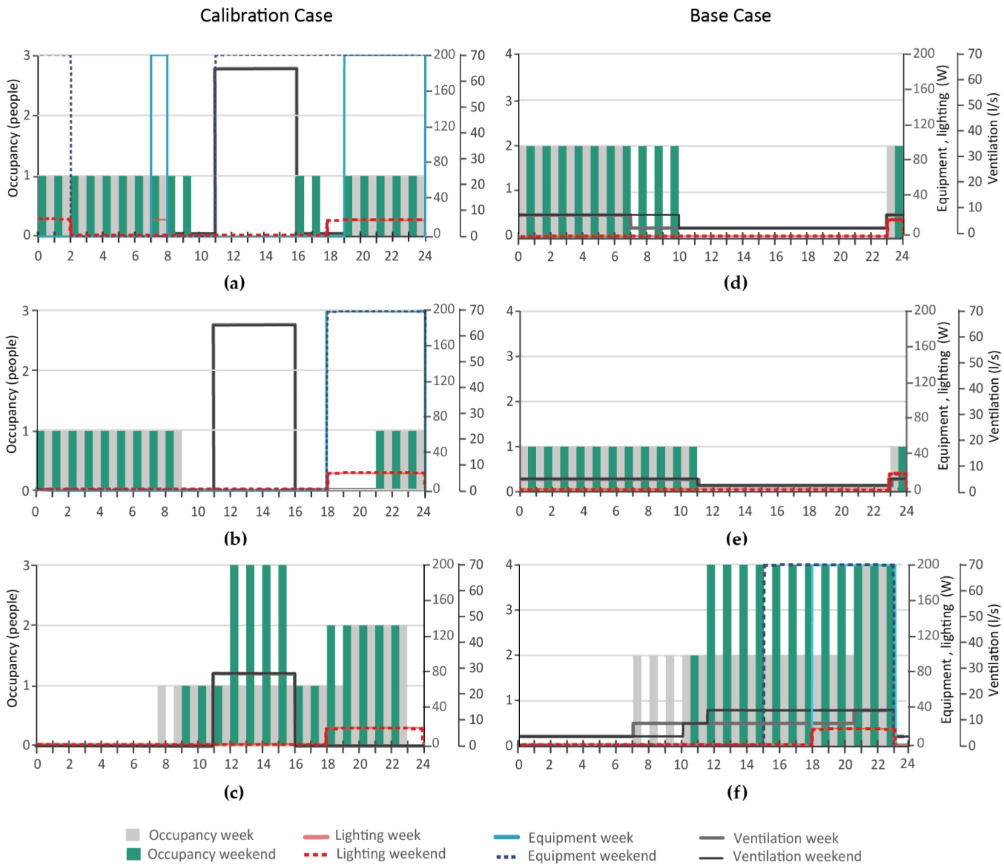

Figure 2. Usage loads and occupation period Calibration case: (**a**) Bedroom 1, (**b**) Bedroom 2, (**c**) Hall; Base Case (**d**), Bedroom 1, (**e**) Bedroom 2–3, (**f**) Living-room.

The calibration results reached a maximum MBE of 3.5%, lower than the 10%, and a maximum CV(RMSE) of 6.7%, which is lower than the 30.0% (See Table 3), thus obtaining a physical model that was validated following the ASHRAE standard, which works as a model to evaluate the initial conditions of the dwelling and the impact of thermal and energy improvements.

Table 3. Calibration results.

Infiltration Rate (n50)	Ground Configuration	Error	Bedroom 1	Living Room	Bedroom 2
8,2 ACH	Ground domain	MBE	3.5%	−1.1%	−1.6%
		RMSE	1.2	0.9	0.7
		CV(RMSE)	6.7%	4.5%	3.9%

2.4. *Thermal and Energy Performance Indicators*

The heating and cooling energy demand was established using the setpoint temperatures of the EN 16798 Standard's static model for Category II [56], with comfort limits for the entire dwelling of 20.0 °C for heating and 26.0 °C for cooling. These setpoints remain constant for all the weather scenarios assessed.

The evaluation of the time in comfort for free-running dwellings was made using adaptive thermal comfort (ATC) models [8]. Although ATC models were mainly developed in offices, they are models that are also a good fit for housing, as inhabitants are free to adapt the type of clothing, as well as to open and close windows to improve the thermal sensation [17]. In the absence of specific models for the local context, international models were used, opting for the ASHRAE 55 standard as it fits the comfort conditions in naturally ventilated buildings [57] and has a higher applicability in social housing [24].

The thermal comfort ranges for the ASHRAE adaptive model are determined by obtaining the neutral temperature (Tn) using the average outdoor operative temperature (Tpma(out)), applying equation 1 and establishing ranges of ± 3.5 °C for a thermal acceptability of 80% and ± 2.5 °C for a thermal acceptability of 90%.

$$\text{Tn} = 0.31 \times \text{T pma(out)} + 17.8. \quad (1)$$

where T pma(out) is the average outdoor operative temperature calculated from the mean outdoor temperature of the 7 previous days, just as equation 2 describes, Te(d − 1) is the average outdoor temperature of the previous day, Te(d − 2) the average outdoor temperature of two days prior and so on, while α is a constant that depends on the weather, assuming α = 0.8.

$$\text{T pma(out)} = (1-\alpha)\,[\text{Te}(d-1) + \alpha \times \text{Te}(d-2) + \alpha^2\,\text{Te}(d-3) + \alpha^3\,\text{Te}(d-4) + \ldots]. \quad (2)$$

The standard states that in order to apply the adaptive comfort limits obtained with these equations, Tpma(out) must be between 10.0 °C and 33.5 °C. When it is outside these values, the comfort limits will assume the constant conditions, taking the values determined by the previous equations for 10.0 °C and 33.5 °C.

2.5. Performance Analysis

The performance analysis of the base case and of cases with improvements, in current and future climatic conditions, was made experimentally using energy simulation results based on the energy demand (static model setpoint of the EN 16798 Standard for Category II) (energy performance) and the percentage of time in thermal comfort when the dwelling operates under free-running, using the ATC of ASHRAE 55-2017 for a thermal acceptability of 80% (thermal performance). The thermal performance was assessed in two rooms with different orientations and uses: Living Room and Bedroom 2.

The weather conditions of Montevideo, characterized by a cold and a warm period, together with the performance analysis of the base case for current and future weather conditions, allowed for determining the baseline and the set of strategies to improve its performance. Identifying that, although the issues associated to low temperatures prevail, the temperature increase foreseen from the CC conditions will increase the cooling demand and will mainly affect discomfort conditions due to heat. Based on the analysis, strategies were defined for winter and summer and also two improvement categories were established, depending on whether the performance is determined by the users or not: construction improvements and operational improvements. Table 4 describes the improvements that are under evaluation. These were determined considering their suitability to solve the problems raised, and common criteria were considered with the standards there are in similar climates and with the materials available in the local market, to limit the ranges being studied of each improvement strategy [58–60].

For winter, the entry of radiation was favored, keeping them free from solar devices and controlling heat losses through the envelope, applying improvements to the thermal transmittance (walls, roof and windows) and in the infiltrations. In all the cases, and as the initial construction has a thermal mass level that is considered favorable, the incorporation of insulation on the envelope was considered on the outside.

For the warm period, shading strategies were considered to avoid solar gains along with night cooling to dissipate the heat accumulated inside (See Table 4). Outdoor PVC roller blinds were considered as solar protections because they allow blocking sun's radiation 100% in all orientations. Ventilation (operational and flow) was determined from the study of the period where discomfort is produced by heat, in the base case, and within those hours where the outdoor temperature is at least

2 °C lower than the indoor temperature, periods where the outdoor air has a cooling capacity. As a result, it was seen that the hours with higher ventilation capacity are those between 10pm and 9am between December and March. The levels to evaluate were set at 2.7 l/s m^2 and 5.3 l/s m^2. For levels over 5.3 l/s m^2, it was confirmed that the improvement in thermal comfort is negligible.

Table 4. Construction and operational improvements to be assessed.

Measures	Level	Characteristics
Construction measures		
Roof insulation (W/m^2K)	0.85 0.61 0.47 0.32	EPS 3.0 cm EPS 5.0 cm EPS 7.0 cm EPS 11.0 cm
Wall insulation (W/m^2K)	0.85 0.61 0.50	EPS 3.0 cm EPS 5.0 cm EPS 6.5 cm
Windows (W/m^2K)	5.80 2.70	SG—aluminium frame DGW—aluminium frame/PVC
Airtightness (ACH)	5.0	Substitution of window with improvements in air permeability
	1.0	Substitution of window with improvements in air permeability combined with weather strips on doors and pipe pass-throughs.
Operational Measures		
Shading	100%	Outdoor PVC roller blinds Active from November to March when Text >19 °C and the incidental solar radiation >120 W/m^2
Ventilation	2.7 l/s·m^2	Night cooling from December to March 10 p.m. to 9 a.m.
	5.3 l/s·m^2	Night cooling between December and March 10 p.m. to 9 a.m.

The DesignBuilder optimization model was used to study the multiple possible combinations among the variables obtaining, as a result, a set formed by 175 cases (Initially there were 457 cases, but those which had minimal differences were discarded). Starting from the simulations run and the resulting set of cases, a total of 14 cases were chosen to assess their thermal and energy performance, 6 cases with individual measures and 8 with combined measures (See Table 7). In Table 7, it can be seen that the cases chosen cover the application of individual and combined improvements with different performance levels, while they also analyzed the levels that can be attained through the current standard. Case A represents the current condition of the dwelling, while B to G represent the application of individual improvements (6 cases): incorporation of solar protection (SP) (Case B), replacement of the window (transmittance and infiltrations (Case C), reduction of infiltrations (Case D), complete change of the window (transmittance, protection and infiltrations) (Case E), modification of the wall transmittance (Case F) and modification of the roof transmittance (Case G). Cases H to O (8 cases) represent the combination of all the improvements with different demand levels. In particular, case H represents the current levels demanded by the governing local standards. All these cases are studied considering solely hygienic cooling [61]. The base case (Case A) and the cases with combined measures (H to O) chosen, were simulated with the night cooling operational measure between December and March from 10 p.m. to 9 a.m., with two cooling flows of 2.7 and 5.3 l/s m^2, generating, in this case, another 16 cases (For example, A1 and A2).

Once the cases chosen for their thermal and energy performance were analyzed in both climate scenarios (current and future), the cases of improvements were assessed for the period of use of the dwelling between 2020 and 2050. Determining by case study and indicator (energy demand and comfort time), the linear function that represents the variation of the indicator in the period, considering time as a variable. Starting from this, the demand and the annual comfort time for each intermediate year was calculated. The sum total of the annual results during the entire period represents the energy demand and comfort time conditions that the dwelling will experience during its use between 2020 and 2050, incorporating the variations these indicators will have due to CC. Figure 3 presents, for the base case, the variation of both indicators during the period and the results for intermediate years obtained through the aforementioned calculations.

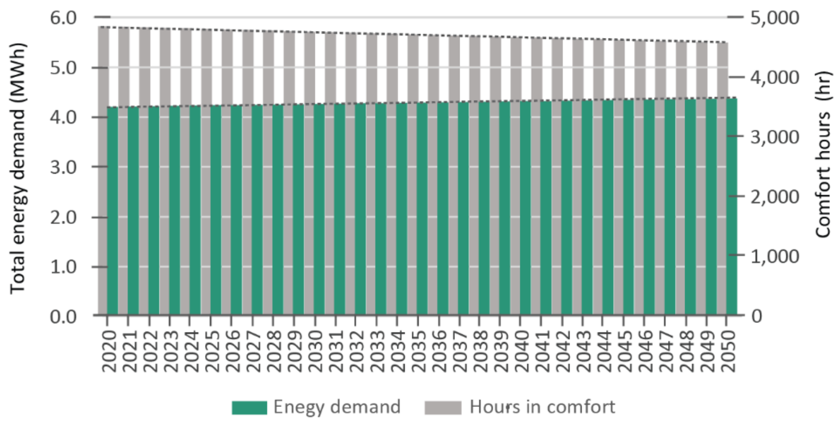

Figure 3. Annual variation of the energy demand and hours in comfort for the 2020–2050 period, in Case L.

The results obtained by both indicators are studied comparatively, determining the suitable set of improvement strategies, considering the mode of use of the dwelling (in free running or with active systems).

3. Results

3.1. Analysis of Energy Demand and Thermal Comfort in Base Case

The thermal and energy conditions of the base case are presented first for the current and future conditions, using the A2 scenario in 2050 for the latter. The results of the energy demand are presented in Table 5 by type of demand and climate scenario. For the current climate, the total annual energy demand for air-conditioning is 12.2 MWh/year (0.19 MWh/m^2 year), distributed into 80.8% for the heating demand and 19.2% for the cooling demand. For the A2 2050 scenario, the total annual demand presents a slight fall, reaching 11.5 MWh/year (0.18 MWh/m^2 year), where 62.2% corresponds to the heating demand and 37.8% to the cooling demand.

Table 5. Base case energy performance by climate scenario (Energy demand).

Scenario	Heating (MWh/Year)	Cooling (MWh/Year)	Total (MWh/Year)
Current	9.8	2.3	12.2
A2 2050	7.1	4.3	11.4

The thermal results indicate for the current climate that the annual time in comfort varies between 45.8% and 48.9% of the annual hours, depending on the room, with discomfort from cold of between 29.5% and 31.3% prevailing, while discomfort from heat corresponds to 22.9% and 21.6%, for the living room and bedroom 2, respectively. Scenario A2 sees a slight fall of the total time in comfort, with 44.1% in the living room and 47.2% in bedroom 2. Discomfort from cold falls to 23.7% and 22.2% and discomfort from heat increases to 32.2% and 30.6% in the living room and bedroom 2, respectively (See Table 6).

Table 6. Base case thermal performance by climate scenario using the ATC Ashrae 55-2017 model.

Scenario	Room	Discomfort Due to Cold (% Annual Hours)	Discomfort Due to Heat (% Annual Hours)	Total Comfort (% Annual Hours)
Current	Living Room Bed 2	31.3% 29.5%	22.9% 21.6%	45.8% 48.9%
A2 2050	Living Room Bed 2	23.7% 22.2%	32.2% 30.6%	44.1% 47.2%

Both analyses present little variation of the total demand and total time in comfort between scenarios, although a variation in their composition is confirmed. As a result of the temperature increase expected in future scenarios, the base case dwelling will experience an increase of 2.0 MWh/year in the cooling demand and an average increase of discomfort from heat of 800 hours, just as occurs in other similar studies [13,22].

3.2. Analysis of Energy Savings

The multivariable combination of the chosen improvements (See Table 4, with the exception of ventilation) was studied for both climate scenarios, obtaining as a result the heating demand (HD), cooling demand (CD) and total demand (TD) by case (See Figure 4). Three sections are identified, starting from a global analysis of the results in both climate scenarios, characterized by a variation in the performance curve. Section 1 (S1) groups the improvement cases of window type, glazing, solar protection and level of infiltrations, without improvements over the enclosures (8 cases). Section 2 (S2) is made up of the individual transmittance improvements of walls or roofs, or one of these in combination with the improvements of S1. In no case of this section are there joint improvements for wall and roof transmittance (53 cases). Finally, Section 3 (S3), has cases that combine all the variables analyzed (114 cases).

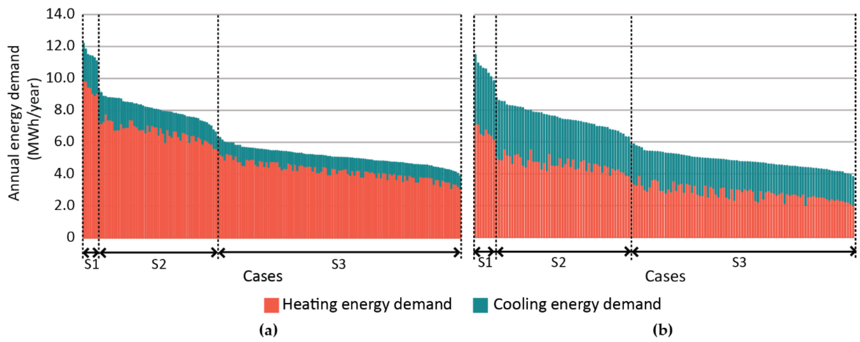

Figure 4. Cooling, heating and total demand for improvement cases. (**a**) Current climate, (**b**) A2 2050 scenario.

Therefore, the identified sections determine the maximum level of reduction of the demand by type of construction improvement. This means that for S1, there is a maximum reduction versus the base case of 9.1% in the current climate and of up to 14.3% in the A2 2050 scenario. S2 varies between a reduction of 24.1% and 44.6% for the current climate and between 23.5% and 45.2% for the A2 2050 scenario. Meanwhile S3 varies between 45.6% and 68.2% and between 48.8% and 66.8% for the current and future climates, respectively.

In addition, the variation by type of demand (heating and cooling) is obtained between the scenarios. For all the cases, in both scenarios, the heating demand is higher than the cooling demand, and both demands have higher levels for S1, followed by the cases of S2 and lower levels in S3.

Continuing with the analysis, 14 cases were chosen to be particularly studied (See Table 7). The cases chosen cover the application of individual and combined improvements with different performance levels, and they also analyze the levels attainable through the current standard.

Table 7. Identification of cases chosen for the study.

Section	Case	U Wall (W/m^2K)	U Roof (W/m^2K)	U Vent. (W/m^2K)	Inf. ACH n50	Solar Prot.	Ventilation (lt/s·per + $l/s{\cdot}m^2$)
				Cases with individual measures			
S1	A (A1,A2)	2.62	3.40	5.8	8.2	-	2.5 + 0.3
	B	2.62	3.40	5.8	8.2	100%	2.5 + 0.3
	C	2.62	3.40	2.7	5	-	
	D	2.62	3.40	5.8	1	-	
	E	2.62	3.40	2.7	5	100%	
S2	F	0.50	3.40	5.8	8.2	-	2.5 + 0.3
	G	2.62	0.32	5.8	8.2	-	
				Cases with combined measures chosen			
S3	H (H1,H2)	0.85	0.85	2.7	8.2	100%	2.5 + 0.3
	I (I1;I2)	0.61	0.47	2.7	5	100%	
	J (J1;J2)	0.50	0.32	2.7	8.2	100%	
	K (K1;K2)	0.50	0.32	2.7	5	100%	
	L (L1;L2)	0.50	0.32	2.7	1	-	
	M (M1;M2)	0.50	0.32	5.8	1	100%	
	N (N1;N2)	0.61	0.32	2.7	1	100%	
	O (O1;O2)	0.50	0.32	2.7	1	100%	

Note: These cases have been simulated also including night cooling between December and March from 10 p.m. to 9 a.m., with two ventilation flows of 2.7 l/s m^2 (A1, H1, I1, J1, K1, L1, M1, N1, O1) and 5.3 $l/s{\cdot}m^2$ (A2, H2, I2, J2, K2, L2, M2, N2, O2).

Figure 5 shows the results obtained from the cases chosen from the study and their relationship with the base case (Case A) for both scenarios. It is assumed that 100% of the demand in each situation corresponds to case A and each improvement case is expressed with regard to this. The cases of A to E, S1, improvement cases without affecting transmittance of enclosures, have a reduction of less than 10% in both scenarios, both for TD and for HD. The analysis of the same cases for CD allows identifying that the cases which include solar protections (B and E) are those which reach a higher reduction versus the base case of 15.6% and 14.5% for the current climate, and of 12.4% and 13.3% for the A2 2050 scenario, case B and E, respectively. The incorporation of night cooling as an individual improvement (case A1 and A2) generates a significant reduction of the CD of 27.9% and 40.4% in the current climate and of 22.0% and 32.0% in the future scenario, for cases A1 and A2, respectively.

Continuing with the individual improvements, it was identified that the chosen cases of S2, individual improvement of the thermal transmittance of walls (Case F) and roofs (Case G), have significantly better performances. For case F, the TD falls by 23.5% and 25.4% in the current and future scenario, respectively, with a higher impact on the HD (current: 27.2%/future: 28.7%) than on the CD (14.8%/17.8%). Case G reaches a reduction of close to 32% of the TD in both scenarios, with a higher impact in the current climate in the reduction of the CD (38.3%) than the HD (30.8%). In future scenarios, its impact is reversed, with a lower reduction of the CD (29.5%) than the HD (32.7%).

The set of combined improvements of cases H to O, from S3, shows that with higher levels of insulation (in walls, roofs and windows) and airtightness, the TD and HD are reduced, producing minimal variations of the CD. On comparatively analyzing case H (combined improvements with minor levels of thermal transmittance of enclosures and higher levels of infiltrations) versus case O (most demanding case in both aspects), it is seen that the reduction of the TD these cases have versus Case A, has a difference of 19.9% and 16.4%; considering HD, the difference is 25.4% and 26.3%;

and evaluating the CD, 3.2% and 0%, for the current and future scenario, respectively. This verifies, as a result, the significant impact of these variables on the heating demand.

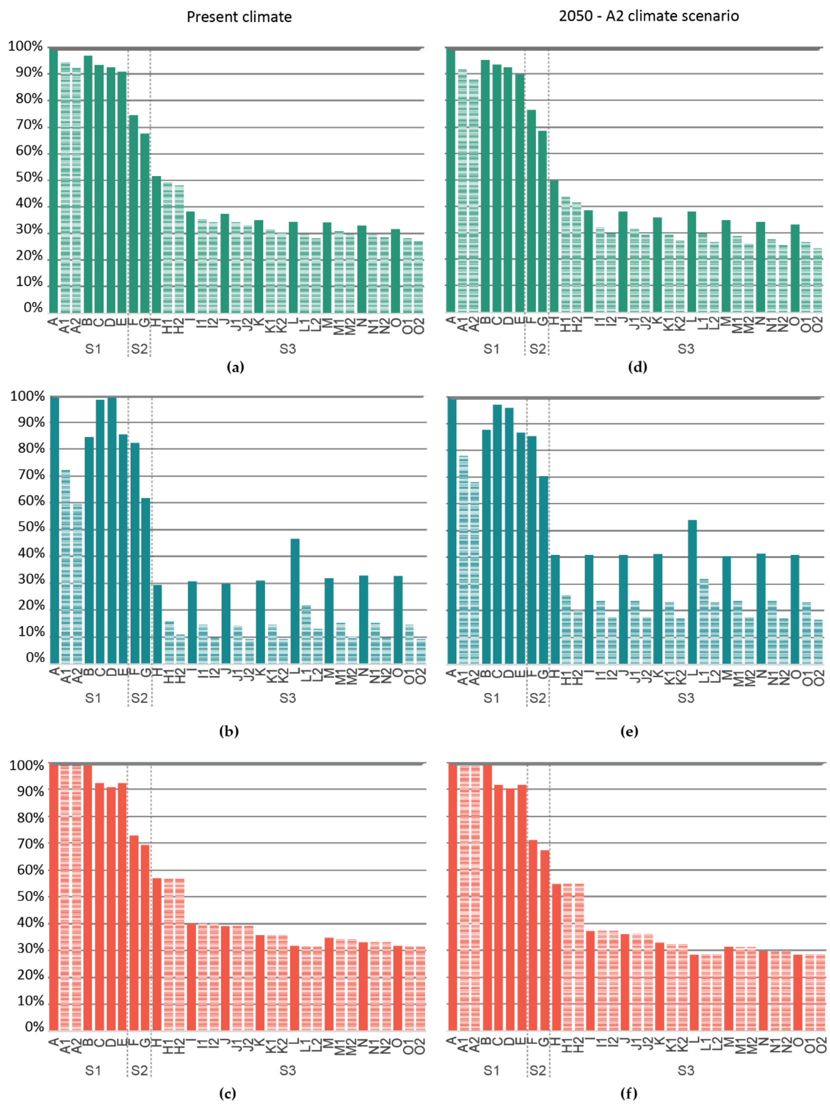

Figure 5. Demand by case study versus the base case, Current climate: (**a**) Total demand, (**b**) Cooling demand, (**c**) Heating demand, A2 Scenario: (**d**) Total demand, (**e**) Cooling demand, (**f**) Heating demand.

Case L is interesting as it represents the improvement of the envelope without using solar protections, standing out through the lower reduction of the CD with levels of 53.2% and 45.8% in the current and future scenario, respectively, while the rest of the cases of T3 reach an average reduction of 70% in the current climate and 60% in that of 2050.

The cases from H to O in a mixed use mode with night cooling during the warm period, have a significant reduction of the cooling demand, with an additional reduction versus the same case without night cooling, in the current climate of between 14.9% and 21.9% for a level of 2.7 l/s/m^2 and between 20.7% and 30.6% for a level of 5.3 l/s/m^2. In the future scenario, the reduction versus the same case without cooling varies between 13.5% and 25.1% for a level of 2.7 l/s m^2 and between 18.2% and 33.4% for 5.3 l/s m^2. This confirms that the cooling remains a suitable strategy, even under the projected temperature increase conditions in the future.

These results agree with the observations made in previous studies for similar climates, like Pérez-Andreu et al. who concluded that for a Mediterranean climate like that of Valencia (even with more demanding initial levels than those studied in this research), the solar protections, increase of thermal insulation and reductions in infiltrations are the strategies with a higher impact on the global demand, while window frames and the type of glazing have a lower incidence [35]. Unlike previous studies, this research has evaluated these strategies for both current and future climates, confirming the results. In another study run in Santa Rosa—Argentina, with a climate in transition between Cfa and Bsk, Filippín et al. showed that the increase in wall and roof insulation has a direct incidence on the reduction of the demand in winter and in summer, and that associated to the improvement in the insulation, higher reductions are achieved with complete shading and night cooling, concluding that the latter is the most important [62]. A difference that is found with this latest research is the impact of the increase in wall insulation without including roof insulation. According to this author, the individual incorporation of this improvement has repercussions on the increase in energy consumption due to the high temperatures reached on the roof in summer. The results obtained in this research demonstrate that the individual increase in wall insulation (Case F) triggers a reduction in the energy demand for both cooling and heating.

3.3. Analysis of Thermal Comfort Based on the Adaptive Comfort Approach

The cases chosen were analyzed under the ASHRAE 55-2017 adaptive comfort model, applying the comfort ranges corresponding to each climate scenario for a thermal acceptability of 80%. Figures 6 and 7 show the results obtained by case and comparatively versus the base case (Case A).

The individual improvements (S1 and S2), cases B to G, have variations below 5% versus the base case in the percentage of time these are in comfort, in discomfort for cold and in discomfort for heat, in both scenarios and in the rooms studied.

On the other hand, night cooling as an individual improvement (Cases A1 and A2) stands out, allowing increasing the percentage of time in comfort versus the base case, in the current climate, of 7.2% and 6.4% for a level of 2.7 l/s m^2 and 10.5% and 10.3% for a level of 53 l/s m^2 for the living room and bedroom 2, respectively. The variation is similar for the future scenario, of 7.0% and 6.4% for a level of 2.7 l/s m^2 and of 11.2% and 10.8% for a level of 5.3 l/s m^2 for the living room and bedroom 2, respectively.

The combined improvements studied, cases H to O, with the exception of case L, had a higher level of insulation and airtightness, little variation of the total time in comfort, with a difference of less than 6% between these cases in both rooms and scenarios.

It was identified that case H, in both scenarios, has the highest discomfort for heat and lowest discomfort for cold and that case O is the opposite. The difference between these two cases for time in discomfort from heat is close to 8% in both rooms under current climate conditions, while, for the future scenario, the rooms have differences of 6.2% in the living room and 12.2% in bedroom 2. As for discomfort due to cold, between case H and case O, the difference for both rooms is 8% under the current climate and of 7.2% in the living room and 6.3% in bedroom 2 for the A2 2050 scenario.

The differences in the comfort results between both rooms increase in the evaluation of the time in discomfort due to heat, allowing identifying the incidence of other factors, like the use and occupation loads or the orientation. These results agree with the observations made by Fosas et al. (2018) that showed that the risk of overheating is associated to multiple design and operation parameters in the dwelling, and not just to the level of insulation [63].

Case L once again is a stand out case of this group, as it had an increase of discomfort due to heat of between 2.7% and 7.1% in both rooms and scenarios, showing how much of an impact the improvement in insulation and airtightness levels can have without a suitable use of solar protections.

On analyzing the set of cases, it can be seen that all the construction improvements reduce discomfort from cold, but some for the living room slightly increase discomfort from heat, and they confirm the importance of the users' behavior regarding ventilation and the correct use of solar protections along the line developed by Van Hooff et al and Escandón et al. [17,18].

It is necessary to point out that a value of α = 0.8 was used for the calculation of the average operating temperature. The α coefficient represents the variation speed at which the average operating temperature responds to external temperature changes. This coefficient has different recommendations depending on the standards. While the European EN16798 standard recommends a value of 0.8, ASHRAE 55 recommends a value of 0.6 for average latitudes. Just as Bienvenido-Huertas et al. (2020) state, there is no consensus regarding the characteristic value of each climate, evidencing in an additional energy analysis, that despite the use of adaptive setpoint temperatures represents an energy saving versus static setpoint temperatures, the α values used in combination with the number of previous days considered, determine the operational temperature and, therefore, directly affect the total energy consumed [64]. In this sense, the results presented are merely orientational, since due to the lack of a local adaptive comfort model, the parameters determined by the international standards are used, among these the α that is suitable for the climate being studied should be known, to obtain more representative results of the comfort parameters of the occupants.

Figure 6. Percentage of time in comfort or discomfort by case study versus the base case, Current climate scenario, Living room: (**a**) Total time in comfort, (**b**) Time in discomfort due to heat, (**c**) Time in discomfort due to cold, Bedroom 2: (**d**) Total time in comfort, (**e**) Time in discomfort due to heat, (**f**) Time in discomfort due to cold.

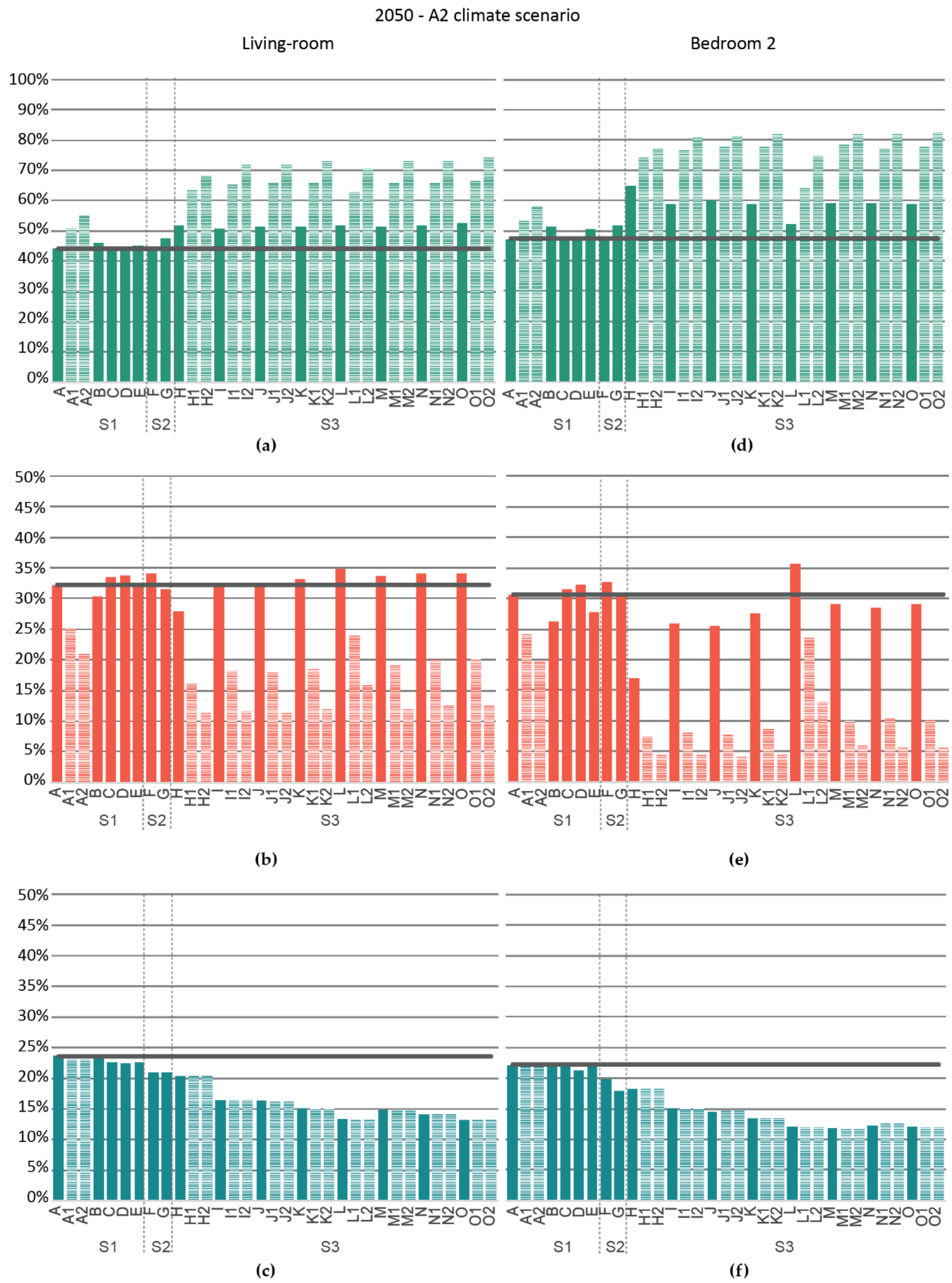

Figure 7. Percentage of time in comfort or discomfort by case study versus the base case, A2 2050 climate scenario, Living room: (**a**) Total time in comfort, (**b**) Time in discomfort due to heat, (**c**) Time in discomfort due to cold, Bedroom 2: (**d**) Total time in comfort, (**e**) Time in discomfort due to heat, (**f**) Time in discomfort due to cold.

3.4. Consumption and Thermal Comfort

The comparative analysis between the time in comfort and total energy demand for the period of use of the dwelling, which is 2020–2050, allowed for evaluating which improvement cases have a better performance for both indicators, that is to say, which improvement cases achieve a reduction in the total energy demand for air-conditioning and increase the total time in comfort (See Figures 8–10).

The results show that the individual improvements studied (transmittance of enclosures and windows, solar protections, airtightness level) have an impact of under 10% over the total time in comfort and that these results differ from the impact on the energy demand, where the individual improvement of insulation in walls (Case F) and roofs (Case G) result in a considerable reduction of the demand, of 24.4% and 31.9%, respectively.

Cases I, J, K, M, N and O with combined improvements have the best performance for both indicators, with a reduction of the demand of between 61.6% and 67.5% and an increase of the time in comfort of close to 16.5% in all the cases in the living room, and between 29.6% and 33.9% in bedroom 2. These cases have an even better performance if the incorporation of night cooling is included (Cases I1, J1, K1, M1, N1, O1, I2, J2, K2, M2, N2, O2), with a reduction of between 66.3% and 74.2% in the energy demand and an increase of the time in comfort of between 47.0% and 64.8% in the living room, and between 57.6% and 68.8% in bedroom 2.

Figure 8 highlights case H, which has similar levels of total time in comfort to the aforementioned cases, with a reduction versus the base case of 16.4% in the living room and 36.2% in bedroom 2. However, the reduction in the demand is a noticeably lower 49.3%.

Meanwhile, the behavior of case L is opposite to that of case H, with a similar level in terms of energy demand, it reduces 63.7% versus the base case, but with a worse performance in terms of comfort, increasing 11.3% versus the base case in the living room and 12.0% in bedroom 2.

Continuing with the case analysis, on comparing their performance for time in discomfort due to heat versus energy demand for cooling, what was seen for the individual case analysis is confirmed, where all the improvements evaluated have a positive impact on the reduction of the CD, but some increase the discomfort for heat, with case L having the highest increase in discomfort (living room: 17.9%/bedroom 2: 15.5%).

Case H is the only one that has a better performance for both rooms and indicators, DR reduction (63.1%) and reduction of the time in discomfort due to heat (living room: 18.8%/bedroom 2: 56.7%).

Cases I, J, K, M, N and O have similar levels in terms of CD (62%). However, in terms of comfort, their performance is notoriously different in each room. In the bedroom, the incidence of these improvements is positive, while in the living-room there is a smaller variation versus the base case, exceeding its discomfort level in some cases (between −2.8% and +8.0%)

Nevertheless, the aforementioned group of cases, with the incorporation of night cooling (Cases I1, J1, K1, M1, N1, O1, I2, J2, K2, M2, N2, O2) are those that reach the best performances in both indicators with minimal differences between cases.

The comparative evaluation of time in discomfort due to cold and the heating demand indicates that cases I, J, K, L, M, N and O are those which have a higher reduction of the heating demand (between 61.1% and 69.7%) and a lower time in discomfort due to cold versus the base case (living room: between 24.3% and 35–36%/bedroom 2: between 24.2% and 39.2%).

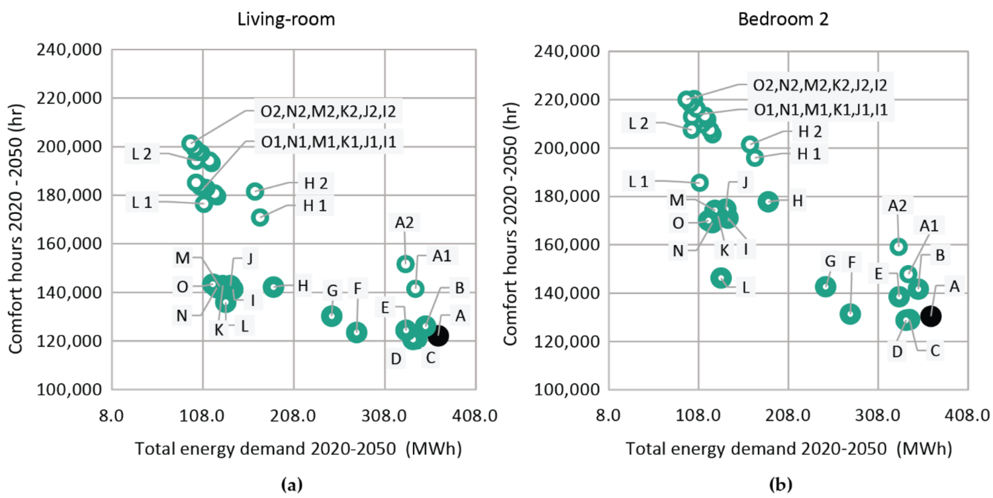

Figure 8. Case evaluation by total time in comfort and total air-conditioning demand for the 2020-2050 period, (**a**) Living room, (**b**) Bedroom 2.

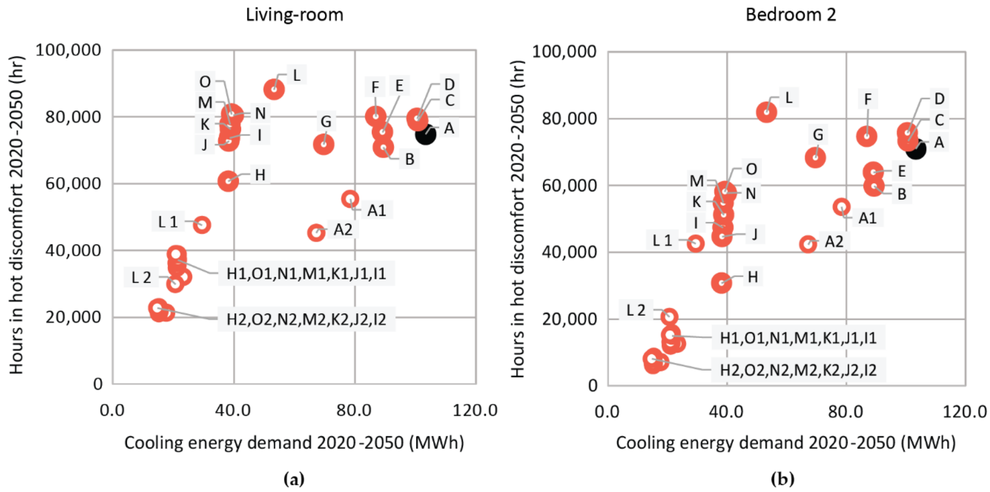

Figure 9. Case evaluation for discomfort due to heat and cooling demand during the 2020-2050 period, (**a**) Living Room, (**b**) Bedroom 2.

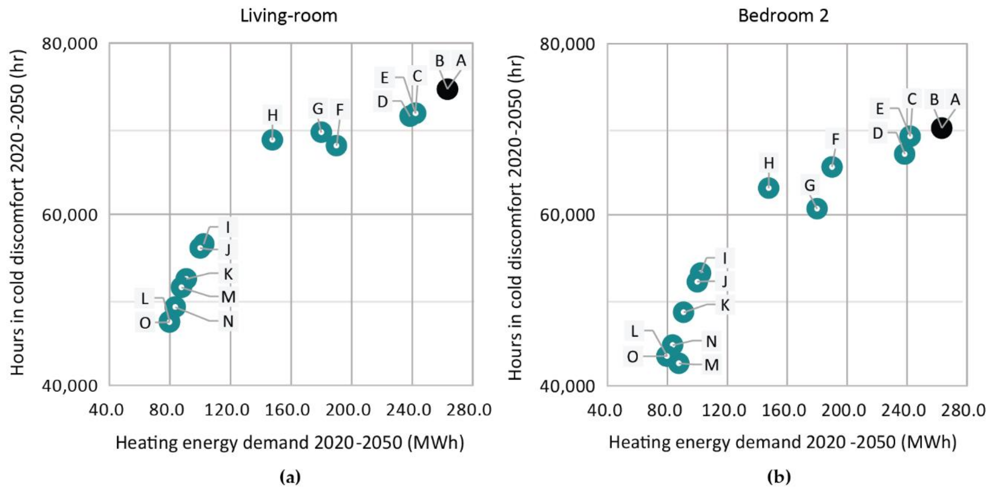

Figure 10. Evaluation of cases for discomfort due to cold and heating demand in the 2020–2050 period, (**a**) Living room, (**b**) Bedroom 2.

4. Conclusions

The effectiveness of energy improvement measures in housing is closely tied to the intensity of use and the thermal comfort demands of the users. Normally, the studies on energy improvement focus on reducing the demand without considering other indicators like the improvement it would have in the thermal conditions of the dwelling. For this reason, it is necessary to provide analyses based on indicators that are capable of quantifying the impact on dwellings that do not use air-conditioning systems or only do so under extreme weather conditions. In addition, most studies into the energy performance of buildings are made using historic weather data and, as such, do not quantify the impact of climate change on the results associated to EE measures. Additionally, those which include the climate change projection are focused on a given year in the future.

The goal of this research has been to assess and prioritize energy improvement measures for existing dwellings in Uruguay. The analysis presented allowed analyzing and prioritizing by assessing both energy demand and thermal comfort using ATC in two climate scenarios: current and future. The main contribution of the proposed methodology is the ability to analyze different retrofit options, comparatively integrating both indicators and their variation from the changes projected in the climate conditions, considering the stage of use of the dwelling.

The results show that the use of both indicators is not equivalent to assessing the performance of improvement strategies and, therefore, special interest must be paid to this when it comes to establishing public energy retrofitting policies. In this regard, the construction improvements with high levels of insulation and airtightness achieve significant reductions of energy demand when active air-conditioning systems are used. However, they can generate overheating conditions in free-running dwellings. The increase in insulation and reduction of infiltration also stand out on having a higher incidence over the total energy demand than over the total time in comfort and that the suitable use of solar protections has an inverse effect.

From the comparative assessment between both indicators for the 2020–2050 period, it is seen that for those cases where their operation is unknown (with active or free-running systems), the cases that reduce the thermal transmittance in walls between 0.50-0.61 W/m^{2}K, in roofs between 0.32–0.47 W/m^2 K, in openings to 2.7 W/m^2 K, with airtightness below 5 ACH n50 and that use solar protections (cases I, J, K, N, O) have significant improvements in both situations over the base case. However, in spite of the fact that they reach similar total performance levels, the study, when broken down into hot and cold conditions, indicates that the use of this level of improvements may not affect the discomfort conditions for heat and may even increase them due to external factors not studied in this research, if operational improvements, in addition to construction improvements, are not applied.

For dwellings that mainly work under free-running, the level of improvement provided by case H with a transmittance in walls and roofs of 0.85 W/m^2 K, in openings of 2.7 W/m^2 K, airtightness of 8.2 ACH n50 and solar protections is the best option to reach the highest increase of time in comfort without risks of generating overheating.

Dwellings that use air-conditioning to reach thermal comfort conditions, achieved a lower energy demand with the improvement levels of Case O, with a transmittance in walls of 0.50 W/m^2 K, in roofs of 0.32 W/m^2 K and in openings of 2.7 W/m^2 K, airtightness of 1 ACH n50 and the use of solar protections.

The operational ventilation parameters and the suitable use of solar protections showed highly positive results to ensure comfort in the dwellings, which underlines the need for improvement strategies to incorporate solar protection elements and to improve the natural ventilation conditions, as well as the necessary training of the users. These factors are particularly important in the context of energy poverty, on being highly effective without costs for the inhabitants, showing why they are essential factors to consider in retrofitting policies for climate conditions like those analyzed.

It is necessary to consider a series of limitations that this study has: first, the study focuses on a single typology, although the case chosen is representative of the existing dwellings in the city, it does not allow for generalizing the results obtained. A higher number of cases is necessary, considering different morphologies, sizes and materialities, for a general evaluation of the housing stock. Second, regarding the study on future climate conditions, one has to consider that the analysis was made for a single emissions scenario, and that the weather prediction models, even though validated, have levels of uncertainty. In addition, the climate files used have their own limitations, they are representations of typical meteorological years without considering extreme events, which leads to considering the results obtained in terms of possible trends. Third, the adaptive comfort analysis was based on the application of an international standard for each climate scenario, the ranges obtained assume a certain adaptability of human beings to future temperatures, which is presented with uncertainty. Additional research is needed that allows for adjusting the model to the local context, including the suitable determination of the α coefficient for the local climate, and especially looking into the adaptability conditions that human beings will experience on facing climate change conditions. However, to reduce the factors of uncertainty of the study, the use as an energy demand indicator can help overcome those factors related to the evolution of HVAC systems.

The methodology implemented allowed for comparing two indicators for the evaluation of improvement strategies during the use stage of the dwellings. Future studies are needed to cover a comprehensive analysis, considering other variables that affect decision-making, like the implementation costs to evaluate the profitability of the cases considered that considers the lifespan or service life of improvements and an analysis of CO_2 emissions.

Author Contributions: All the authors contributed equally to the present research. All authors have read and agreed to the published version of the manuscript.

Funding: The authors would like to thank the Grupos I+D—2018 Project N°62 of the Scientific Research Sector Commission, University of the Republic (CSIC-UdelaR) for financing the travel expenses that made this research possible.

Acknowledgments: The authors would like to acknowledge the research group "Confort ambiental y pobreza energética (+CO-PE)" of the University of the Bío-Bío for supporting this research.

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

Nomenclature

ACH	Air Changes Per Hour
ATC	Adaptive Thermal Comfort
A2	Family of Scenarios from the IPCC Special Report on Emission Scenarios
CC	Climate Change
CD	Cooling Demand
CV(RMSE)	Square Root Coefficient Variation of the Mean Bias Error
EC	Energy Consumption
EE	Energy Efficiency
FP	Fuel Poverty
HVAC	Heating, ventilation, and air conditioning
IPCC	Intergovernmental Panel on Climate Change
MBE	Mean Bias Error
PVC	Polyvinyl Chloride
S1	Section 1
S2	Section 2
S3	Section 3
C	Total Demand
TMY	Typical Meteorological Year
Tn	Neutral Temperature
T Pma(out)	Average Outdoor Operative Temperature

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