Title: Influence of the type of thermostat on the energy saving obtained with adaptive setpoint temperatures: analysis in the current and future scenario

Abstract:
Building energy performance should be improved to reduce the impact of climate change. The energy saving potential has been recently proved with adaptive setpoint temperatures. However, the accuracy of thermostats hinders the achievement of the energy saving obtained in previous studies. For this reason, this paper studies the influence of three types of thermostats according to their configuration accuracy: 0.1, 0.5, and 1 ºC. Two case studies (with and without retrofitting) were analysed in three cities in the current scenario, in 2050, and in 2100. The results showed that the implementation of adaptive setpoint temperatures in thermostats of 0.1 ºC virtually obtains the same savings as the direct application of thermal comfort limits. Nevertheless, obtaining considerable energy savings in the other two thermostats depends on the type of energy consumption, climate, and the category of the thermal comfort model. The application of adaptive setpoint temperatures in air conditioning systems obtains energy savings greater than 40%, regardless of the type of thermostat and category, whereas in heating systems, only the category III obtains energy savings with old thermostats.

Keywords:
Energy saving; thermostat; adaptive thermal comfort model; residential buildings.

1. Introduction

The decarbonisation of the building stock by 2050 is among the main goals established by the European Union in the roadmap to move to a low carbon economy [1]. The building stock plays an important role in the greenhouse gas emissions generated by its high energy consumption [2,3]. Among other factors, this high energy consumption is produced because most building stock was built before the first standards on energy efficiency of each country [4,5]. The improvement of building stock energy performance is crucial to achieve the sustainable goals established by the European Union and to eliminate other problems related to high building energy consumption, such as energy poverty [6–8].

Likewise, the energy consumption of Heating, Ventilating and Air Conditioning (HVAC) systems should be reduced [9,10] because these systems are the main source of building energy consumption, even above electrical household appliances and lighting systems. For this purpose, the implementation of energy conservation measures (ECMs) improving either the envelope or HVAC systems is the most used measure [11,12]. However, implementing this type of ECM could be unfeasible for low-income families, such as those in energy poverty [13]. Moreover, improving the energy performance of a building by implementing new technologies does not necessarily reduce greenhouse gas emissions because of the rebound effects that could be generated by the changes of users' behaviour [14]. Users could think that, with the energy improvement of their building, HVAC systems (e.g., heating systems) could be more used, thus generating a greater energy consumption than that generated before renovating the building [15].

ECMs focused on users' behaviour should therefore be established, thus using HVAC systems coherently and sustainably. One of the possibilities to achieve an energy saving and to guarantee a sustainable use of HVAC systems is by establishing appropriate setpoint temperatures [16,17] because the setpoint temperature and the energy consumption are directly related [18]. This measure has been widely analysed in many studies conducted in office buildings, such as Parry et al. [19], Wan et al. [20], and Spyropoulos and Balaras [21]. Great savings in the energy consumption were obtained by modifying setpoint temperatures of up to 4 ºC. However, the possibility of implementing these modifications in residential buildings is not analysed, although their application in low-income families could imply a huge potential as these ECMs are economic [22]. Nevertheless, previous research studies focused on office buildings used an approach of static thermal comfort models in which users are passive subjects with no thermal adaptation. Adaptive thermal comfort models are suitable for spaces where people do not use air-conditioning systems, and these models could be more appropriate for residential buildings. These models consider individuals' thermal adaptability depending on the external climate variations and establish the adaptive comfort limits based on daily thermal oscillations [23]. The implementation of adaptive thermal comfort models could achieve significant energy savings through various measures [24], including the use of adaptive setpoint temperatures. These adaptive setpoint temperatures involve using the upper and lower limit values of the adaptive thermal comfort model between which the internal operative temperature should oscillate: the lower limit is used for the heating setpoint temperature, and the upper limit for the cooling setpoint temperature. Several studies have analysed the possibility of applying these setpoint temperatures in both office buildings and residential buildings: (i) Yun et al. [25] analysed the possibility of applying adaptive thermal comfort models in the use of air conditioning systems in office buildings located in South Korea. The results showed percentage reductions of up to 22% in the energy consumption; (ii) in another similar study, Sánchez-García et al. [17] analysed the possibility of using adaptive thermal comfort models in an office building located in Seville (Spain) in the current scenario and in the A2 climate change scenario. The use of adaptive setpoint temperatures saved the energy consumption between 36.7 and 59.5%; (iii) this study was continued by Bienvenido-Huertas et al. [26], in which the office building was analysed in all the cities of the Iberian Peninsula. The results showed the relationship between the type of climate and the energy saving achieved. Thus, zones with greater cooling energy consumption obtained the greatest energy saving values; (iv) as for residential buildings, Sánchez-Guevara Sánchez et al. [27] assessed the possibility of using monthly adaptive setpoint temperatures in 3 residential buildings located in Seville, Madrid, and Avila. Savings between 20 and 80% were obtained in the energy consumption; and (v) in other two studies conducted in these cities, Sánchez-García et al. [28,29] assessed the possibility of modifying the operational profile of the Spanish Building Technical Code by using adaptive setpoint temperatures. With these modifications, savings between 10 and 46% were obtained.

Some studies have also analysed and optimised adaptive setpoint temperatures. Bienvenido-Huertas et al. [30] analysed the optimal weight (α-value) to calculate the running mean outdoor temperature in Avila, Madrid and Seville, thus achieving additional energy savings with new setpoint temperatures. Furthermore, Sánchez-García et al. [29] analysed the possibilities of applying an adaptive operational pattern in the Spanish Building Technical Code through different approaches. Despite of this, the research studies applied the upper and lower limits of adaptive thermal comfort models directly. However, these limits could obtain values up to 3 decimals that are unlikely to be configurable in the thermostats of the existing buildings. Thus, the direct use of the adaptive limit value could be difficult to be implemented in actual thermostats, with limited accuracy values. Knowing the expected energy savings in actual cases is something of a challenge when applying an adaptive operational pattern. As a result, the limitations related to the implementation of adaptive setpoint temperatures should be analysed because of the accuracy of the thermostat. This study analyses the variations in the energy saving when implementing the adaptive setpoint temperatures in three types of thermostats according to their accuracy: 0.1, 0.5, and 1 ºC. Therefore, the results of this study represent an inflection point as it assesses from an actual perspective the energy savings obtained with the adaptive setpoint temperatures. The use of the values obtained directly from the adaptive limits could present limitations in actual thermostats (with limited accuracy values). This type of approach has not been used in any previous study on the application of adaptive strategies.

Two existing buildings with a deficient behaviour of the envelopes were assessed, determining the energy consumption with both an operational approach of a static thermal comfort model and adaptive thermal comfort models (also including the direct use of upper and lower limits, as in other research studies). The analyses were performed in the main cities assessed in the scientific literature (Avila, Madrid, and Seville), both in the current scenario and in future scenarios (2050 and 2100), using the A2 climate change scenario.

This paper is structured as follows: Section 2 explains in detail the adaptive thermal comfort model used and the approaches analysed; Section 3 includes the methodology by describing the climate zones and the case studies; Section 4 presents and discusses the results; and Section 5 summarises the main conclusions.

2. Adaptive thermal comfort model and the approaches analysed for the adaptive setpoint temperatures

The thermal comfort approaches to regulate the operative temperature of indoor spaces could be divided into two types: (i) the static thermal comfort model based on the research studies by Fanger [31], and (ii) adaptive thermal comfort models [32]. Regarding the former, the studies by Fanger are based on the heat exchange between the environment and the user. The main principle of these models is that the user is the passive subject without the possibility of adaptation, and the operational conditions are independent of climate variations. These models have been widely used through ISO 7730 [33] to establish the operational conditions of indoor spaces. This type of thermal comfort model is different from the adaptive thermal comfort model, in which the user is the active subject and can adopt adaptive measures to achieve thermal comfort [34].

An essential aspect in adaptive thermal comfort models is that the upper and lower limits between which the internal operative temperature should oscillate depend on the external temperature variations. To determine these limits, a mathematical model of the adaptive thermal comfort models mainly based on linear regressions should be used. There are various studies and standards that develop adaptive thermal comfort models. In Europe, the standard that develops the adaptive thermal comfort model is EN 16798-1:2019 [35]. This standard establishes 3 categories of thermal comfort according to the type of user or building (see Figure 1): category I is related to users with low thermal adaptation (e.g., elderly or children), category II is for new buildings, and category III is for existing buildings. Nonetheless, these categories go from lower to greater thermal adaptation, and the application depends on the actual possibilities of users' adaptation. To determine the upper and lower limits between which the internal operative temperature should oscillate, the standard uses a variable which is common in other adaptive thermal comfort models, i.e., the running mean outdoor temperature (T_{rm}) (Eq. 1)). T_{rm} is obtained by a weighted average of the mean outdoor temperature of the n previous days ($T_{ext,d-n}$). After determining T_{rm}, upper and lower limits are calculated through the linear regressions related to the category used (see Eqs. (2) – (7)). For this purpose, the value of T_{rm} should be between 10 and 30 ºC; if not, the adaptive thermal comfort model could not be applied (i.e., the user could not be more adapted).

$$T_{rm} = (T_{ext,d-1} + 0.8T_{ext,d-2} + 0.6T_{ext,d-3} + 0.5T_{ext,d-4} + 0.4T_{ext,d-5} + 0.3T_{ext,d-6} + 0.2T_{ext,d-7})/3.8 \quad [ºC] \tag{1}$$

$$Upper\ limit\ (Category\ I) = 0.33 \cdot T_{rm} + 20.8 \quad [ºC] \quad (10 \leq T_{rm} \leq 30) \tag{2}$$

$$Lower\ limit\ (Category\ I) = 0.33 \cdot T_{rm} + 15.8 \quad [ºC] \quad (10 \leq T_{rm} \leq 30) \tag{3}$$

$$Upper\ limit\ (Category\ II) = 0.33 \cdot T_{rm} + 21.8 \quad [ºC] \quad (10 \leq T_{rm} \leq 30) \tag{4}$$

$$Lower\ limit\ (Category\ II) = 0.33 \cdot T_{rm} + 14.8 \quad [ºC] \quad (10 \leq T_{rm} \leq 30) \tag{5}$$

$$Upper\ limit\ (Category\ III) = 0.33 \cdot T_{rm} + 22.8 \quad [ºC] \quad (10 \leq T_{rm} \leq 30) \tag{6}$$

$$Lower\ limit\ (Category\ III) = 0.33 \cdot T_{rm} + 13.8 \quad [ºC] \quad (10 \leq T_{rm} \leq 30) \tag{7}$$

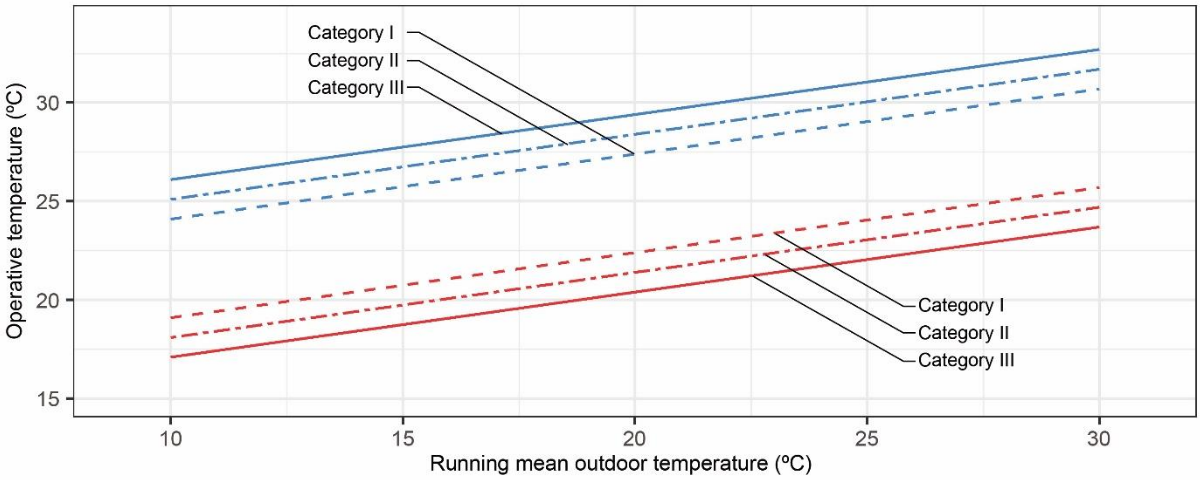

Figure 1. Upper and lower limits of each category from EN 16798-1:2019.

Energy saving measures based on the modification of users' operational patterns could be established with these adaptive thermal comfort models. One of the measures recently analysed is the use of adaptive setpoint temperatures (i.e., setpoint temperatures whose value is the upper or lower limit of the adaptive thermal comfort model) [28,29]. Thus, modifying the setpoint temperature of the thermostat of a dwelling could significantly save energy consumption due to the saving obtained in the hourly heating or cooling degrees [24]. However, adaptive thermal comfort limits have been directly applied without considering the limitations related to the accurate configuration of thermostats. By way of example, when T_{rm} has a value of 19.6 ºC, the lower limit of category I would be 22.268 ºC and the upper limit of category I would be 27.268 ºC. However, configuring a thermostat with this temperature value is something of a challenge. The accuracy levels of thermostats are usually limited, from 1 to 0.1 ºC in the most recent thermostats. For this reason, 4 approaches were assessed to apply the adaptive setpoint temperatures (see Figure 2). The approaches were designed according to the types of thermostat: (i) the first approach (AP-1) corresponded to the direct application of the thermal comfort limits without establishing accuracy limitations in the thermostat (like in previous studies); (ii) the second approach (AP-2) was designed for thermostats with an accuracy of 0.1 ºC; (iii) the third approach (AP-3) corresponded to thermostats with an accuracy of 0.5 ºC; and (iv) the fourth thermostat (AP-4) corresponded to the application of the adaptive setpoint temperatures in thermostats with an accuracy of 1 ºC. An essential aspect when applying adaptive setpoint temperatures in the thermostats of the approaches AP-2, AP-3 and AP-4 was that the operative temperature should be always guaranteed to be within the thermal comfort limits. For this purpose, the heating adaptive setpoint temperatures were modified by increasing the lower limit value according to the limitations of the thermostat (e.g., for the lower limit value of 22.268 ºC, a value of 22.3 ºC was used with AP-2, 22.5 ºC with AP-3, and 23 ºC with AP-4), whereas in the case of the cooling adaptive setpoint temperatures, the upper limit value was decreased according to the limitations of the thermostat (e.g., for the upper limit value of 27.268 ºC, a value of 27.2 ºC was used with AP-2, 27 ºC with AP-3, and 27 ºC with AP-4). Moreover, the accuracies of the thermostats were the same in all temperatures.

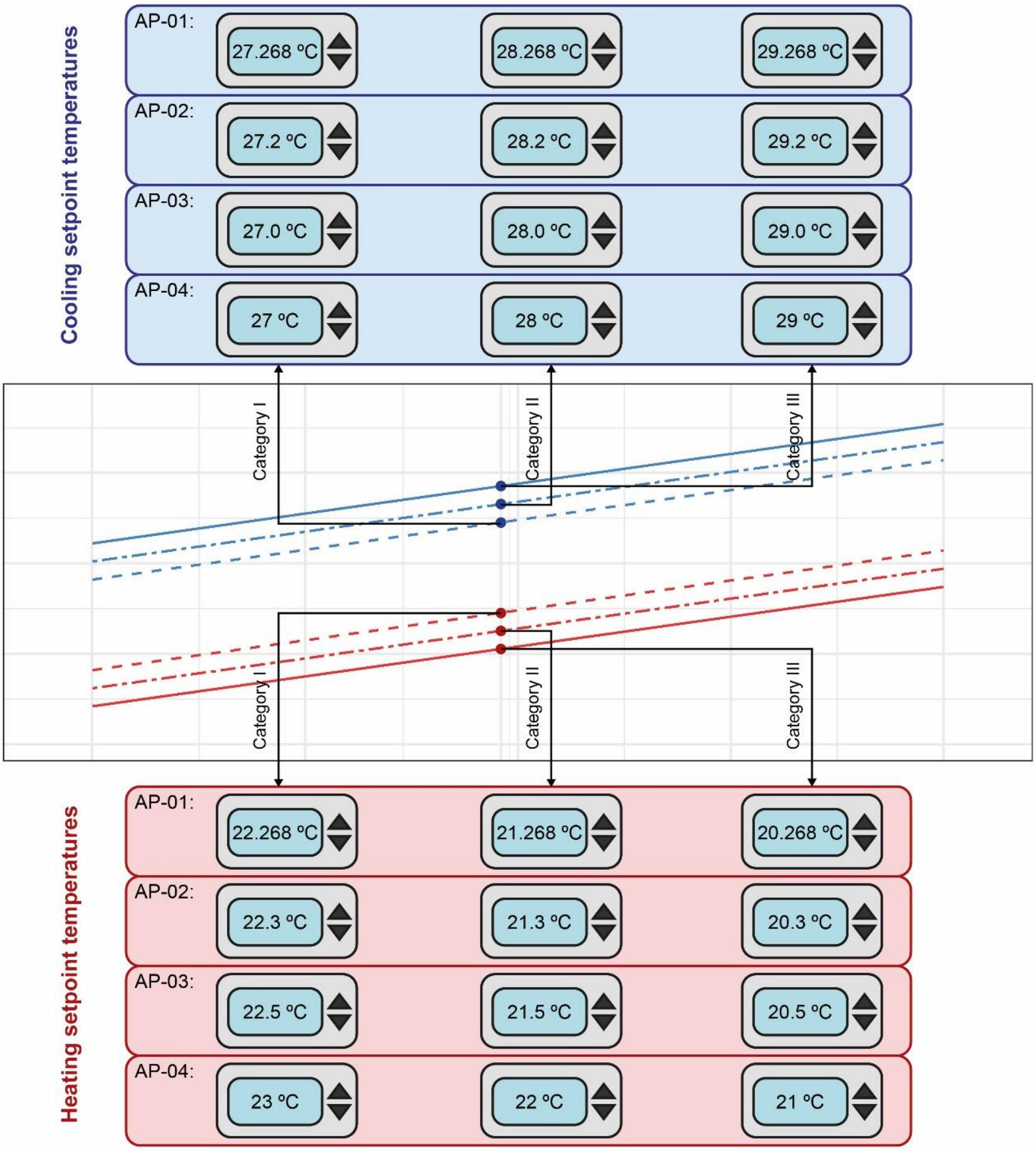

Figure 2. Explanatory scheme of the approaches analysed for the adaptive setpoint temperatures according to the accuracy of the thermostat.

3. Material and methods

3.1. Climate zones

Several climate zones were analysed to study the influence of the limitations of the thermostat on the energy saving obtained with the adaptive setpoint temperatures. To select these climate zones, the studies on the application of adaptive setpoint temperatures were analysed [16,27–30]. All these studies analysed case studies located in Spain and were based on the climate classification established by the Building technical Code in Spain (CTE in Spanish) to select the cities analysed. In short, the climate classification from the CTE is based on the winter and summer climate severity of each city in Spain and establishes a classification for each severity: (i) for the winter climate severity, a letter from A (zones with mild climate) to E (zones with greater severity) is established; and (ii) for the summer climate severity, a numeric classification from 1 (zones with cool summers) to 4 (zones with hot summers) is established. The climate classification of each region of the country is obtained by combining these two classifications for seasonal severities. Based on this classification, the previous studies analysed 3 climate zones which were also related to various climates of the Köppen-Geiger classification [36]: B4 (corresponding to Csa class), D3 (corresponding to BSh class), and E1 (corresponding to Csb class). Seville was selected for B4, Madrid for D3, and Avila for E1.

Moreover, most studies on adaptive setpoint temperatures have analysed the effectiveness of these strategies in future climate change scenarios. In particular, the A2 scenario of emissions developed by the Intergovernmental Panel on Climate Change (IPCC) has been used [37]. This scenario is among the most unfavourable scenarios predicted from the evolution of climate throughout the 21st century [38], with an increase of the external temperature up to 5.4 ºC by the end of that century.

Climate data were also analysed in the A2 scenario of the zones B4, D3, and E1. The years selected were 2050 and 2100 because the former is the year established to fulfil the goals of reducing greenhouse gas emissions, and the latter is the year corresponding to the end of the 21st century. To obtain climate data, the METEONORM software was used as it obtains climate data of any location and scenario (current and future) through stochastic processes [39].

3.2. Case studies and energy simulation

Two case studies were used (see Figure 3). Buildings representing the building stock built before 1979 were chosen for two reasons: (i) most buildings of the country belong to this building period [40]; and (ii) the buildings built in this period are characterized by having envelopes with poor thermal properties [41]. In addition, the poor thermal properties of the envelope (mainly characterized by a high thermal transmittance) imply that these buildings have a high energy demand, thus contributing to energy poverty [42,43]. For these reasons, two case studies from the building period before 1979 were selected. Both buildings have four dwellings per floor. The thermal properties of the façade are presented in Table 1. Moreover, windows have a simple glazing, with a thermal transmittance of 5.7 W/(m^{2}K) and a metallic framework without thermal bridge break. The buildings were modelled and simulated with DesignBuilder (see Figure 3). DesignBuilder is a graphical interface of the energy simulation program EnergyPlus (developed by the U.S. Department of Energy). EnergyPlus is one of the simulation programs with the best performance to study building energy performance. The HVAC systems of the buildings are heat pumps. For this study, the performance of the heat pumps was 2.1 in heating and 2.0 in cooling. For the energy analysis, an intermediate floor of each building was assessed to dismiss the effect generated by the heat transfers through the roof and the floor, similarly to the study by Sánchez-García et al. [44]. The fourth floor of the case study A was analysed, as well as the second floor of the case study B. Likewise, the possibility that the case studies would have improved their façade was assessed (see Table 1): (i) for the case study A, the application of an external thermal insulation composite system (ETICS) was considered, and (ii) for the case study B, the air gap was filled with insulating material. A total of 4 case studies were analysed. These case studies were analysed with the various climate data indicated in Subsection 3.1.

As for building load profile, the load profile for residential buildings included in the CTE was used (see Table 2). The use of this profile was based on two reasons: (i) it represents how the Spanish family units use buildings [45]; and (ii) it is used by studies related to this subject, such as Sánchez-Guevara Sánchez et al. [27] or Sánchez-García et al. [28,29]. This profile is characterized by distinguishing two load periods: one for weekdays and another for weekends. As for the latter, the profile considers that equipment in the dwelling are more used. In addition, Table 3 presents the types of operational patterns analysed and the setpoint temperatures related to each. These operational patterns were developed with the CTE operational patterns. The four approaches of the adaptive thermal comfort model indicated in Section 2 were analysed: AP-1, AP-2, AP-3, and AP-4. Each was applied to each category of the adaptive thermal comfort model. An aspect to be stressed is the value that should be used when the adaptive thermal comfort model is not applicable (i.e., when T_{rm} is lower than 10 ºC or greater than 30 ºC). In these cases, the limit values obtained by the linear regressions were applied (e.g., when T_{rm} was lower than 10 ºC, the value of the upper and lower limits was determined considering a T_{rm} of 10 ºC). Furthermore, an operational pattern of the HVAC systems based on a static thermal comfort model was analysed. The static setpoint temperatures of this operational pattern were obtained with the operational profile for residential buildings of the CTE, also used in other studies [27–29].

Models were calibrated according to the criteria of ASHRAE Guideline 14 [46]. For this purpose, measurements were made in situ in the study cases. The measurements lasted 1 month in each case study, dividing the monitoring into 15 days in summer and 15 days in winter (Figure 4). These measurements were made throughout 2017 and 2018. Moreover, a TESTO 435-2 datalogger and an ALMEMO 2590-4AS datalogger with type K thermocouples (temperature measurement range between -20 and 70 °C, resolution of 0.1 °C and accuracy of ±0.1 °C) were used. After monitoring and simulating data, two statistical parameters of the ASHRAE Guideline 14 were assessed: the Normalized Mean Bias Error ($NMBE$) (Eq. 8) and the Coefficient of Variation of the Root Mean Square Error ($CV(RMSE)$) (Eq. 9). For hourly validations, the limit values were 10% for $NMBE$ (in absolute values) and 30% for $CV(RMSE)$ [46]. The results of the validation process showed compliance with the standard's validation criteria: $NMBE$ was 6.11 in case study A, and 8.19% in case study B, while $CV(RMSE)$ obtained values of 6.38% and 9.29% in case studies A and B, respectively.

$$NMBE = \frac{1}{\bar{m}} \cdot \frac{\sum_{i=1}^{n}(m_i - s_i)}{n - p} \tag{8}$$

$$CV(RMSE) = 100 \cdot \frac{1}{\bar{m}} \cdot \sqrt{\frac{\sum_{i=1}^{n}(m_i - s_i)^2}{n - p}} \tag{9}$$

Figure 3. Case studies.

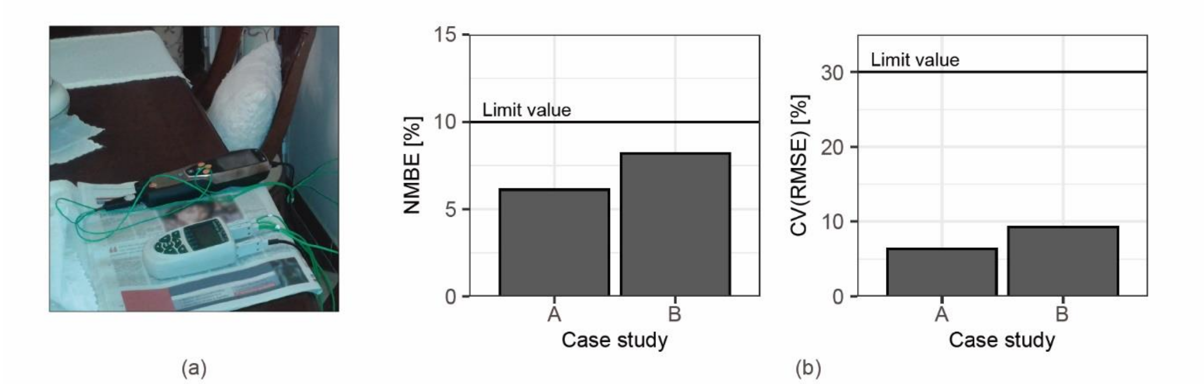

Figure 4. Validation process of the energy simulation models: (a) photograph of the measurement carried out in case study B, and (b) values obtained in the statistical parameters considered by the ASHRAE Guideline 14.

Table 1. Thermal properties of the façades of the case studies.

Case study	Thermal transmittance ($W/(m^2K)$)	Layer	Thickness (m)	Thermal conductivity (W/(mK))	Thermal resistance (m^2K/W)
Case study A (without retrofitting)	2.088	Mortar cement	0.020	0.70	-
		Concrete block	0.200	0.923	-
		Mortar cement	0.020	0.70	-
		Gypsum plaster	0.020	0.57	-
Case study B (without retrofitting)	1.291	Mortar cement	0.015	0.70	-
		Solid brick	0.115	0.85	-
		Mortar cement	0.010	0.70	-
		Air gap	0.060	-	0.18
		Hollow brick	0.070	0.32	-
		Gypsum plaster	0.020	0.57	-
Case study A (with retrofitting)	0.425	Insulation	0.060	0.032	-
		Mortar cement	0.020	0.70	-
		Concrete block	0.200	0.923	-
		Mortar cement	0.020	0.70	-
		Gypsum plaster	0.020	0.57	-
Case study B (with retrofitting)	0.405	Mortar cement	0.015	0.70	-
		Solid brick	0.115	0.85	-
		Mortar cement	0.010	0.70	-
		Insulation	0.060	0.032	-
		Hollow brick	0.070	0.32	-
		Gypsum plaster	0.020	0.57	-

Table 2. Profiles with the load distribution according to the CTE.

Loads		Time period					
		0:00 – 6:59	07:00 – 14:59	15:00 – 17:59	18:00 – 18:59	19:00 – 22:59	23:00 – 23:59
Sensible load (W/m^2)	Weekdays	2.15	0.54	1.08	1.08	1.08	2.15
	Weekend	2.15	2.15	2.15	2.15	2.15	2.15
Latent load (W/m^2)	Weekdays	1.36	0.34	0.68	0.68	0.68	1.36
	Weekend	1.36	1.36	1.36	1.36	1.36	1.36
Lighting (W/m^2)	Weekdays and weekend	0.44	1.32	1.32	2.20	4.40	2.20
Equipment (W/m^2)	Weekdays and weekend	0.44	1.32	1.32	2.20	4.40	2.20

Table 3. Operational profiles of the HVAC systems.

Model	Standard and category	Approach	Type	Range	Setpoint temperature [ºC]								
					January - May			June - September			October - December		
					23:00-6:59	07:00-14:59	15:00-22:59	23:00-6:59	07:00-14:59	15:00-22:59	23:00-6:59	07:00-14:59	15:00-22:59
Static model	CTE	-	Cooling	all	-	-	-	27	-	25	-	-	-
		-	Heating	all	17	20	20	-	-	-	17	20	20
Adaptive model	EN 16798-1:2019 (category I)	AP-1	Cooling	T_{rm}<10	-	-	-	Min (Eq. (2))	-	Min (Eq. (2))	-	-	-
		AP-2		10≤T_{rm}≤30	-	-	-	Eq. (2)	-	Eq. (2)	-	-	-
		AP-3		T_{rm}>30	-	-	-	Max (Eq. (2))	-	Max (Eq. (2))	-	-	-
		AP-4	Heating	T_{rm}<10	Min (Eq. (3))			-	-	-	Min (Eq. (3))		
				10≤T_{rm}≤30	Eq. (3)			-	-	-	Eq. (3)		
				T_{rm}>30	Max (Eq. (3))			-	-	-	Max (Eq. (3))		
	EN 16798-1:2019 (category II)	AP-1	Cooling	T_{rm}<10	-	-	-	Min (Eq. (4))	-	Min (Eq. (4))	-	-	-
		AP-2		10≤T_{rm}≤30	-	-	-	Eq. (4)	-	Eq. (4)	-	-	-
		AP-3		T_{rm}>30	-	-	-	Max (Eq. (4))	-	Max (Eq. (4))	-	-	-
		AP-4	Heating	T_{rm}<10	Min (Eq. (5))			-	-	-	Min (Eq. (5))		
				10≤T_{rm}≤30	Eq. (5)			-	-	-	Eq. (5)		
				T_{rm}>30	Max (Eq. (5))			-	-	-	Max (Eq. (5))		
	EN 16798-1:2019 (category III)	AP-1	Cooling	T_{rm}<10	-	-	-	Min (Eq. (6))	-	Min (Eq. (6))	-	-	-
		AP-2		10≤T_{rm}≤30	-	-	-	Eq. (6)	-	Eq. (6)	-	-	-
		AP-3		T_{rm}>30	-	-	-	Max (Eq. (6))	-	Max (Eq. (6))	-	-	-
		AP-4	Heating	T_{rm}<10	Min (Eq. (7))			-	-	-	Min (Eq. (7))		
				10≤T_{rm}≤30	Eq. (7)			-	-	-	Eq. (7)		
				T_{rm}>30	Max (Eq. (7))			-	-	-	Max (Eq. (7))		

4. Results and discussion

First, the energy consumption related to the use of static operational patterns was analysed. Figure 5 shows the annual heating, cooling, and total energy consumption obtained in the combinations of case study and climate zone in the current scenario, in 2050, and in 2100. In the case studies without improvements in the envelope, the climate zones had different tendencies in energy consumption according to their winter and summer climate severity. The climate zone B4 in the current scenario obtained the lowest heating energy consumption and the greatest cooling energy consumption, and in the climate zone E1, the sole contribution was heating energy consumption. Likewise, there was an ascending order in the total energy consumption as the climate zone had greater winter severity, with an increase between 13,600.81 and 15,478.66 kWh in the total energy consumption of E1 in comparison with that of B4. Moreover, the effect on energy consumption by improving the envelope was also interesting, with different tendencies according to the type of energy consumption. The improvement of the façade clearly decreased the heating energy consumption (with reductions between 1,940.68 and 13,085.89 kWh), but the reductions were low in cooling energy consumption (obtaining reductions with maximum values of 3,442.83 kWh), so this improvement was not an effective energy saving measure to reduce cooling energy consumption. This aspect became more important in the future tendencies of building energy performance throughout the 21st century. In this regard, the external temperature with the A2 scenario of emissions increased cooling energy consumption, although its impact on the total energy consumption depended on the climatic severity of the region: (i) the warm climatic zone (B4) was characterized by an increase in the total energy consumption of 475.83 kWh in 2050 and of 7,829.89 kWh in 2100; and (ii) the less warm climatic zones (D3 and E1), although cooling energy consumption was increased between 949.37 and 10,241.83 kWh in future scenarios, the total energy consumption decreased due to the savings obtained in heating.

The use of a static operational pattern would not allow adequate energy performance to be achieved in retrofitted case studies. However, modifying the operational pattern with an adaptive approach could be an opportunity to reduce the energy consumption of the case studies. Table 4 presents the percentage deviation obtained in the current scenario between the adaptive energy consumption with the AP-1 (i.e., the approach on which the existing studies are based) and the static energy consumption. The application of the adaptive setpoint temperatures obtained various energy savings according to the category used from EN 16708-1:2019 in the case studies without retrofitting. Category I was related to a lower energy saving due to the greater approach of the upper and lower limits, even increasing heating energy consumption. Despite this increase, the saving obtained in cooling energy consumption (between 55.3 and 84.9%) saved the total energy consumption between 2.1 and 32.1%. Thus, savings could also be achieved by applying a category with a lower thermal adaptation of users, and these savings could be increased if users could apply category II or III. In this regard, the application of these two categories obtained savings between 2 and 44.8% in the heating energy consumption, between 67.5 and 99.2% in cooling energy consumption, and between 14.2 and 70.3% in the total energy consumption. With respect to the case studies with retrofitting, the application of adaptive strategies achieved saving percentages similar to those obtained with the case studies without retrofitting: (i) category I obtained heating energy savings between 0.1 and 4.7% (with increases in energy consumption for heating in zone B4), cooling energy savings between 58.7 and 86.9%, and total energy savings between 10.7 and 48.4%, (ii) category II obtained heating energy savings between 16.3 and 35.5%, cooling energy savings between 69.1 and 98.2%, and total energy savings between 26.7 and 65.8%, and (iii) category III obtained heating energy savings between 32.5 and 77.4%, cooling energy savings between 77.5 and 99.9%, and total energy savings between 39.7 and 79.7%.

Nonetheless, the results of combining retrofitting and adaptive setpoint temperatures with respect to the case study without retrofitting with static setpoint temperatures achieved significant savings (Table 5). The improvement of the envelope and the use of the adaptive setpoint temperatures achieved savings between 26.6 and 91.9% in heating, between 61.2 and 100% in cooling, and between 35.5 and 86.8% in the total energy consumption. Variations in energy savings depend on the type of category used, with the combination of retrofitting with adaptive setpoint temperatures of category III obtaining the greatest energy savings. In addition, these values were similar in future years: in 2050 there was an average variation of 3.66% in the percentage deviations obtained in comparison with the current scenario (Table 6), and in 2100 this average value was 10.43% (Table 7).

As mentioned in previous sections, the actual possibilities of applying adaptive setpoint temperatures depend on the accuracy of the thermostat. The application of the adaptive setpoint temperatures with values greater than one decimal is therefore something of a challenge in actual applications. For this reason, 3 approaches were analysed to apply the adaptive setpoint temperatures according to the accuracy of the thermostat: AP-2 when the thermostat had an accuracy of 0.1 ºC, AP-3 when the thermostat had an accuracy of 0.5 ºC, and AP-4 when the thermostat had an accuracy of 1 ºC. The adaptive setpoint temperatures were used with these approaches to always guarantee users' thermal comfort. The heating setpoint temperatures were obtained by increasing the lower limit value according to the accuracy of the thermostat (e.g., a value of 22.5 ºC in AP-3 was used for a lower limit value of 22.268 ºC), and the cooling setpoint temperatures were obtained by decreasing the upper limit value. These variations also varied the building energy consumption, with a significant increase from the application of AP-2 to the application of AP-4. This aspect is shown by the point clouds included in Figures 6 and 7., which represent the variation obtained in the hourly energy consumption of the accuracy approaches of the thermostat in comparison with the approach not considering the accuracy in the thermostat (AP-1). The following average increases in the hourly energy consumption were found by analysing the results: (i) with AP-2, heating energy consumption increased between 0.002 and 0.007 kWh, and cooling energy consumption between 0.001 and 0.005 kWh; (ii) with AP-3, the energy consumption increased between 0.038 and 0.145 kWh, and cooling energy consumption between 0.02 and 0.033; and (iii) with AP-4, heating energy consumption increased between 0.08 and 0.31 kWh, and cooling energy consumption between 0.004 and 0.079 kWh.

The AP-2 did not significantly increase the hourly energy consumption, unlike the other approaches. These variations influenced the annual energy consumption obtained by the adaptive approaches (Figures 8-10). AP-2, AP-3, and AP-4 increased cooling and heating energy consumption in comparison with that obtained with AP-1. In the current scenario, an average increase in annual heating energy consumption of 1.02, 10.47 and 22.44% was obtained with AP-2, AP-3, and AP-4, respectively, and in the annual cooling energy consumption, the increase percentages were greater: 5.09% with AP-2, 41.40% with AP-3, and 76.44% with AP-4. The percentages of the variation of heating energy consumption in 2050 and 2100 were like those obtained in the current scenario, with variations between 0.06 and 6.22%. However, there were variations in cooling energy consumption because of the accuracy of the thermostat in 2050 and 2100, as the percentage deviation tended to decrease in comparison with AP-1. In 2050, there was a percentage variation in cooling energy consumption of 2.69% with AP-1, 15.16% with AP-3, and 38% with AP-4, and in 2100, there was a percentage variation in cooling energy consumption of 0.88% with AP-1, 8.02% with AP-3, and 6.22% with AP-4. Thus, the application of adaptive setpoint temperatures presented limitations according to the type of thermostat available in the dwelling. The application of adaptive strategies in dwellings with a thermostat with an accuracy of 0.1 ºC almost obtained the energy savings presented in previous research studies. However, their use in dwellings with HVAC systems with lower accuracy in the configuration of the thermostat could limit the effectiveness of this energy saving strategy. This aspect is shown by the heatmaps with the percentage deviation achieved with the energy consumption of the approaches of the adaptive setpoint temperatures in comparison with the energy consumption of the static approach (Figures 11-13).

As for heating energy consumption, category I did not obtain savings with respect to the operational pattern of static setpoint temperatures used. Thus, the limitations related to the accuracy of the thermostat could significantly increase energy consumption, even doubling it in some cases (AP-4 in the climate zone B4 of the year 2100). Category II decreased energy consumption in comparison to the static setpoint temperatures, and its application in HVAC systems with an accuracy of 0.5 ºC or 1 ºC could increase energy consumption between 0.2 and 31.9%. In this regard, category III only guaranteed an energy saving with all types of thermostat according to the possible accuracy, obtaining a minimum value of 7.8% in the saving of heating energy consumption (AP-4) and a saving greater than 15% in the other two approaches (AP-2 and AP-3). As for the saving in cooling energy consumption, the application of adaptive setpoint temperatures with all the approaches obtained appropriate energy saving values. The use of adaptive operational patterns achieved savings in cooling energy consumption greater than 40%, regardless of the type of thermostat. Finally, as for the total energy consumption, there were cases with category I in which the application of adaptive setpoint temperatures in HVAC systems with thermostat with low accuracy did not obtain energy savings (an increase between 0.5 and 6.5% was obtained in these cases). These increase results were related to the zones in which heating energy consumption significantly contributed to the total energy consumption (i.e., climate zones D3 and E1). However, the application of the adaptive setpoint temperatures in thermostats with low accuracy achieved significant savings in the climate zone B4 (greater than 18.4%). Nonetheless, the application of categories II or III was the most appropriate framework to use the adaptive setpoint temperatures to guarantee the energy saving in all case studies with thermostats with low accuracy. Nevertheless, the application of these measures in thermostats with an accuracy of 0.1 ºC obtained energy savings almost identical to those obtained with the theoretical approach of the adaptive setpoint temperatures (AP-1). Therefore, an economic assessment by engineers and architects about the suitability of renovating the HVAC system of the case study and implementing another with greater accuracy of the thermostat would ensure a greater effectiveness to apply these strategies. As for low-income families (such as those at energy poverty risk), the use of the adaptive setpoint temperatures obtained with categories II or III from EN 16798-1:2019 would be the most appropriate option to save energy consumption without an economic investment that could affect the remaining economic expenses of the family unit.

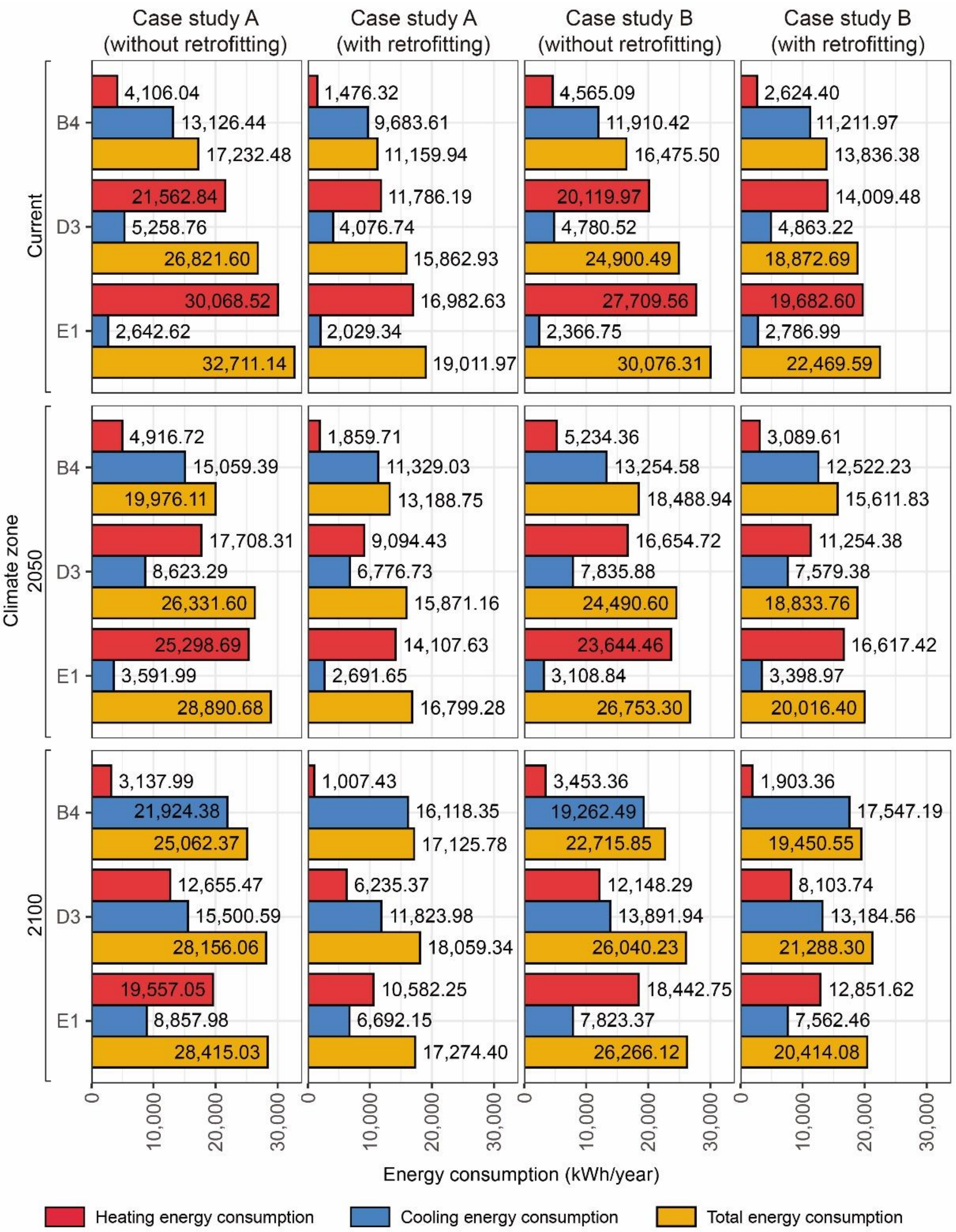

Figure 5. Energy consumption obtained with an operational pattern of HVAC systems based on static setpoint temperatures.

Table 4. Deviation percentage between the energy consumption obtained with the static setpoint temperatures and that obtained with the adaptive setpoint temperatures of the AP-1 in the current scenario. Negative values correspond to a decrease in the energy consumption, and positive values to an increase.

Case study	Category	Deviation percentage (%)								
		B4			D3			E1		
		Heating	Cooling	Total	Heating	Cooling	Total	Heating	Cooling	Total
Case study A	I	41.9	-55.3	-32.1	11.0	-59.2	-2.8	3.8	-84.9	-3.4
(without	II	-6.0	-67.5	-52.9	-4.4	-78.5	-18.9	-8.5	-95.3	-15.5
retrofitting)	III	-44.8	-78.3	-70.3	-23.0	-92.9	-36.7	-22.6	-99.2	-28.8
Case study A	I	27.1	-59.9	-48.4	5.8	-61.3	-11.4	-1.6	-86.9	-10.7

(with	II	-35.5	-70.5	-65.8	-16.9	-81.2	-33.4	-18.1	-98.2	-26.7
retrofitting)	III	-77.4	-80.0	-79.7	-36.9	-95.0	-51.8	-32.5	-99.9	-39.7
Case study B	I	40.5	-56.2	-29.4	11.2	-58.2	-2.1	4.7	-83.8	-2.2
(without	II	-2.0	-68.1	-49.8	-4.3	-77.4	-18.4	-7.3	-94.4	-14.2
retrofitting)	III	-38.9	-78.3	-67.4	-22.3	-91.8	-35.6	-21.2	-99.0	-27.3
Case study B	I	27.8	-58.7	-42.3	-0.1	-58.8	-15.2	-4.7	-76.3	-13.6
(with	II	-20.1	-69.1	-59.8	-16.3	-70.6	-30.3	-20.2	-91.9	-29.1
retrofitting)	III	-57.3	-77.5	-73.7	-33.7	-86.0	-47.2	-33.2	-98.4	-41.3

Table 5. Percentage of deviation between the energy consumption obtained with adaptive setpoint temperatures and retrofitting with respect to the case study without retrofitting and with static setpoint temperatures. Negative values correspond to a decrease in energy consumption, and positive values to an increase.

Case study	Category	Deviation percentage (%)								
		B4			D3			E1		
		Heating	Cooling	Total	Heating	Cooling	Total	Heating	Cooling	Total
Case study A	I	-54.3	-70.4	-66.6	-42.2	-70.0	-47.6	-44.4	-90.0	-48.1
	II	-76.8	-78.2	-77.9	-54.6	-85.5	-60.6	-53.8	-98.6	-57.4
	III	-91.9	-85.3	-86.8	-65.5	-96.2	-71.5	-61.9	-100.0	-65.0
Case study B	I	-26.6	-61.2	-51.6	-30.4	-58.1	-35.7	-32.3	-72.1	-35.5
	II	-54.1	-70.9	-66.2	-41.7	-70.1	-47.2	-43.3	-90.5	-47.0
	III	-75.5	-78.9	-77.9	-53.9	-85.8	-60.0	-52.6	-98.1	-56.1

Table 6. Deviation percentage between the energy consumption obtained with the static setpoint temperatures and that obtained with the adaptive setpoint temperatures of the AP-1 in the 2050. Negative values correspond to a decrease in the energy consumption, and positive values to an increase.

Case study	Category	Deviation percentage (%)								
		B4			D3			E1		
		Heating	Cooling	Total	Heating	Cooling	Total	Heating	Cooling	Total
Case study A	I	38.3	-56.3	-33.0	15.8	-58.4	-8.5	4.2	-71.4	-5.2
(without	II	-3.4	-67.9	-52.1	-4.6	-72.0	-26.7	-9.4	-87.3	-19.1
retrofitting)	III	-39.3	-78.0	-68.5	-25.6	-84.3	-44.8	-24.5	-96.2	-33.4
Case study A	I	25.3	-57.7	-46.0	7.4	-63.7	-22.9	-1.6	-75.0	-13.4
(with	II	-31.5	-68.7	-63.4	-18.3	-75.3	-42.7	-19.1	-90.6	-30.6
retrofitting)	III	-71.1	-78.3	-77.3	-40.2	-85.7	-59.6	-34.3	-98.7	-44.7
Case study B	I	37.1	-57.1	-30.5	16.2	-58.1	-7.6	5.1	-69.5	-3.6
(without	II	-0.3	-69.1	-49.6	-4.4	-71.8	-26.0	-7.6	-85.8	-16.7
retrofitting)	III	-34.2	-79.1	-66.4	-24.5	-83.9	-43.5	-22.5	-95.4	-31.0
Case study B	I	24.6	-58.2	-41.8	3.3	-60.9	-22.5	-4.7	-65.7	-15.0
(with	II	-17.8	-68.8	-58.7	-17.6	-71.0	-39.1	-21.1	-81.1	-31.3
retrofitting)	III	-53.0	-78.0	-73.1	-37.0	-80.4	-54.5	-34.8	-92.2	-44.5

Table 7. Deviation percentage between the energy consumption obtained with the static setpoint temperatures and that obtained with the adaptive setpoint temperatures of the AP-1 in the 2100. Negative values correspond to a decrease in the energy consumption, and positive values to an increase.

Case study	Category	Deviation percentage (%)								
		B4			D3			E1		
		Heating	Cooling	Total	Heating	Cooling	Total	Heating	Cooling	Total
Case study A	I	53.8	-47.8	-35.0	22.9	-53.8	-19.3	10.1	-58.6	-11.3
(without	II	2.5	-58.0	-50.4	-2.2	-64.8	-36.7	-6.6	-71.0	-26.7
retrofitting)	III	-41.4	-67.7	-64.4	-26.7	-74.2	-52.8	-25.5	-82.3	-43.2
Case study A	I	44.2	-43.7	-38.5	11.7	-55.8	-32.5	3.7	-60.7	-21.3
(with	II	-35.3	-54.9	-53.7	-18.0	-66.7	-49.9	-19.4	-74.2	-40.7
retrofitting)	III	-82.6	-65.0	-66.1	-45.2	-76.0	-65.4	-39.8	-85.0	-57.3
Case study B	I	52.1	-48.7	-33.3	21.9	-54.1	-18.6	11.6	-58.1	-9.2
(without	II	4.8	-58.9	-49.3	-1.3	-65.2	-35.4	-4.9	-71.3	-24.7
retrofitting)	III	-36.2	-68.8	-63.8	-24.5	-74.5	-51.2	-23.5	-82.6	-41.1
Case study B	I	44.3	-47.2	-38.2	9.2	-54.6	-30.3	-2.8	-59.3	-23.8
(with	II	-13.7	-57.2	-53.0	-15.9	-65.2	-46.4	-19.0	-69.8	-37.8
retrofitting)	III	-58.5	-66.5	-65.7	-38.2	-74.2	-60.5	-36.5	-79.9	-52.5

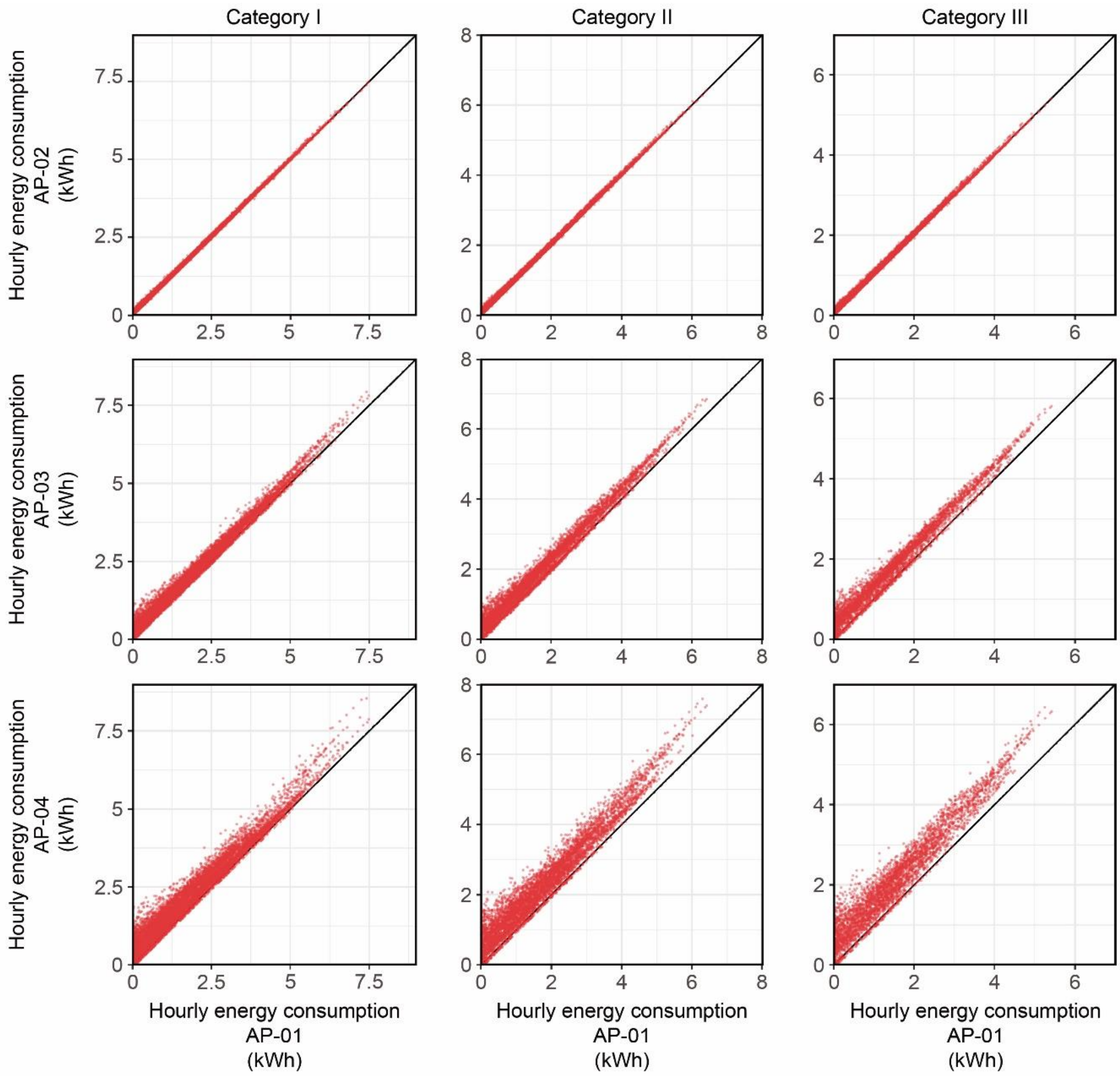

Figure 6. Cloud points of the hourly heating energy consumption obtained with the theoretical approach of adaptive setpoint temperatures (AP-1) and those obtained by applying the adaptive setpoint temperatures in thermostats with accuracy limitations (AP-2, AP-3, and AP-4). This figure shows the results obtained in all the case studies of the climate zone B4 in the current scenario.

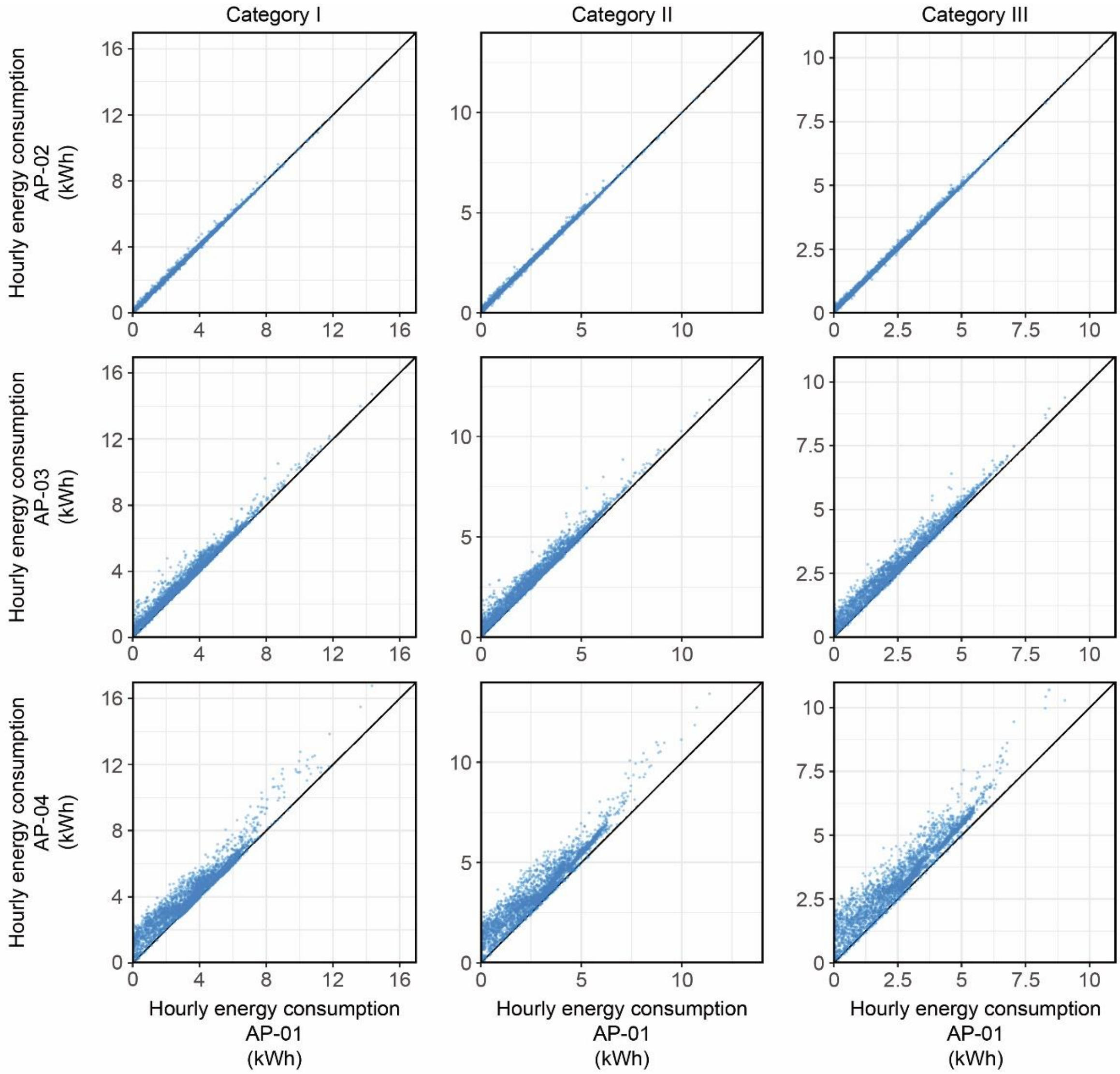

Figure 7. Cloud points of the hourly cooling energy consumption obtained with the theoretical approach of adaptive setpoint temperatures (AP-1) and those obtained by applying the adaptive setpoint temperatures in thermostats with accuracy limitations (AP-2, AP-3, and AP-4). This figure shows the results obtained in all the case studies of the climate zone B4 in the current scenario.

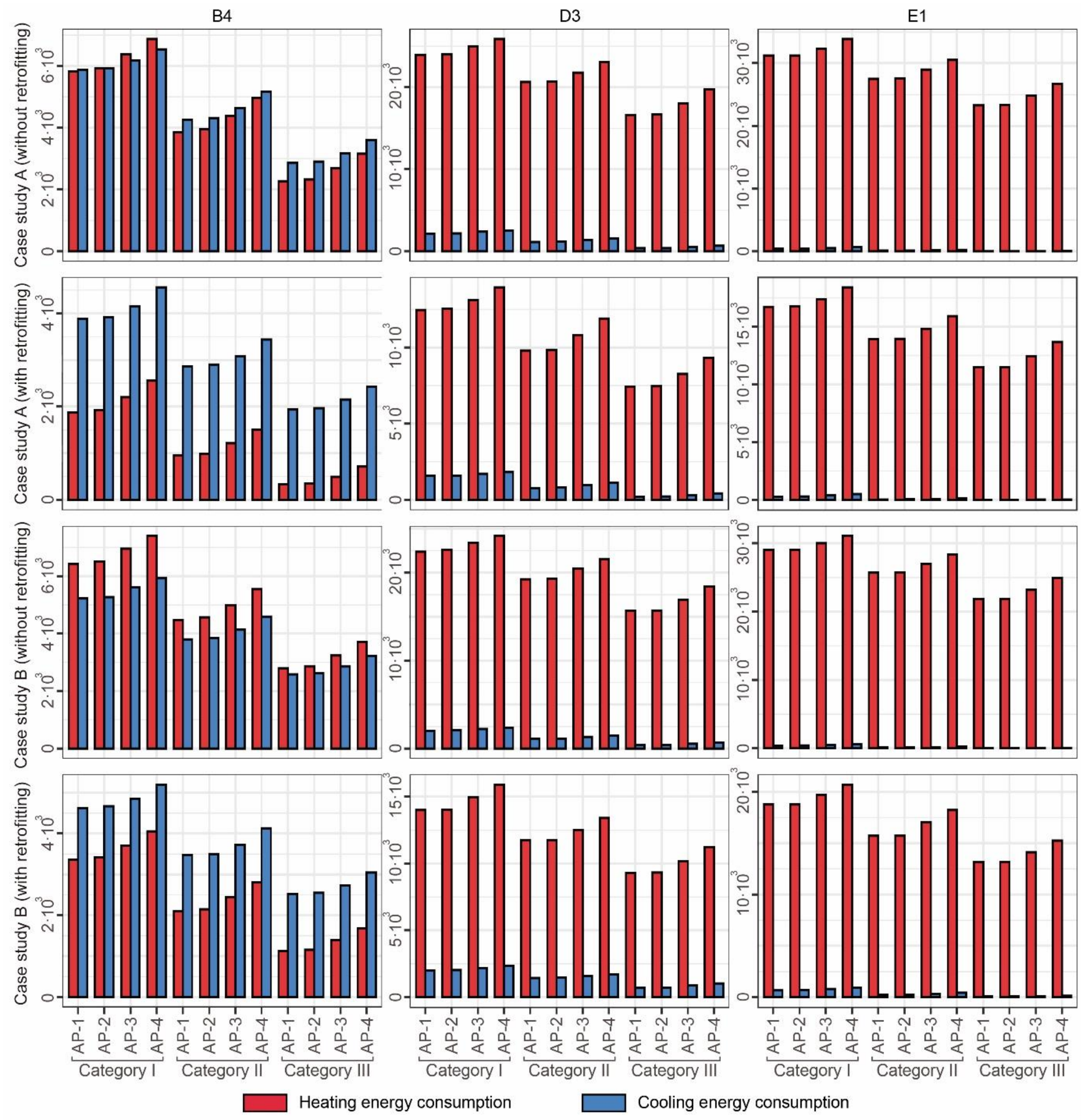

Figure 8. Distribution of the annual energy consumption obtained in the case studies with the approaches of adaptive setpoint temperatures in the current scenario.

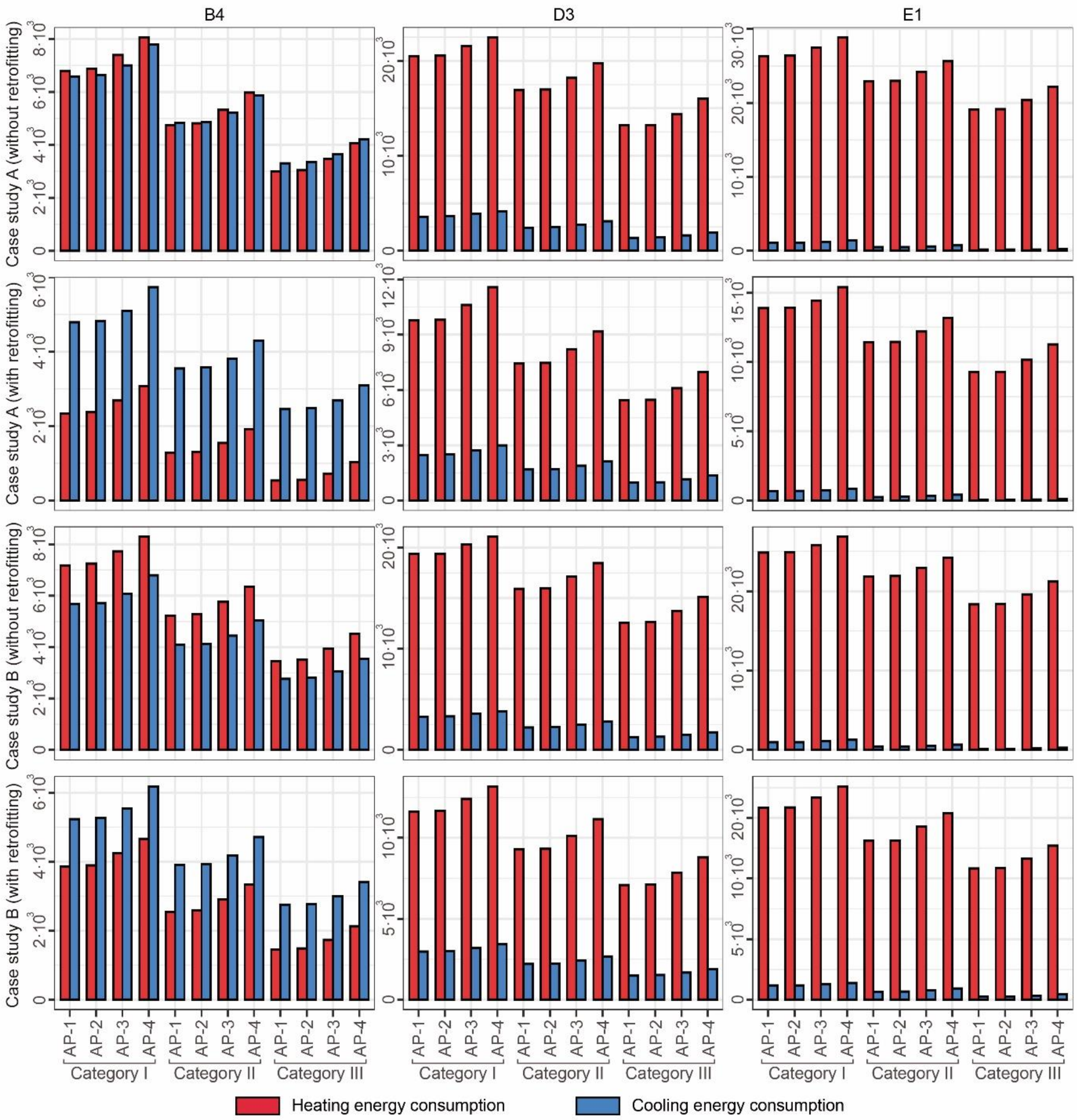

Figure 9. Distribution of the annual energy consumption obtained in the case studies with the approaches of adaptive setpoint temperatures in 2050.

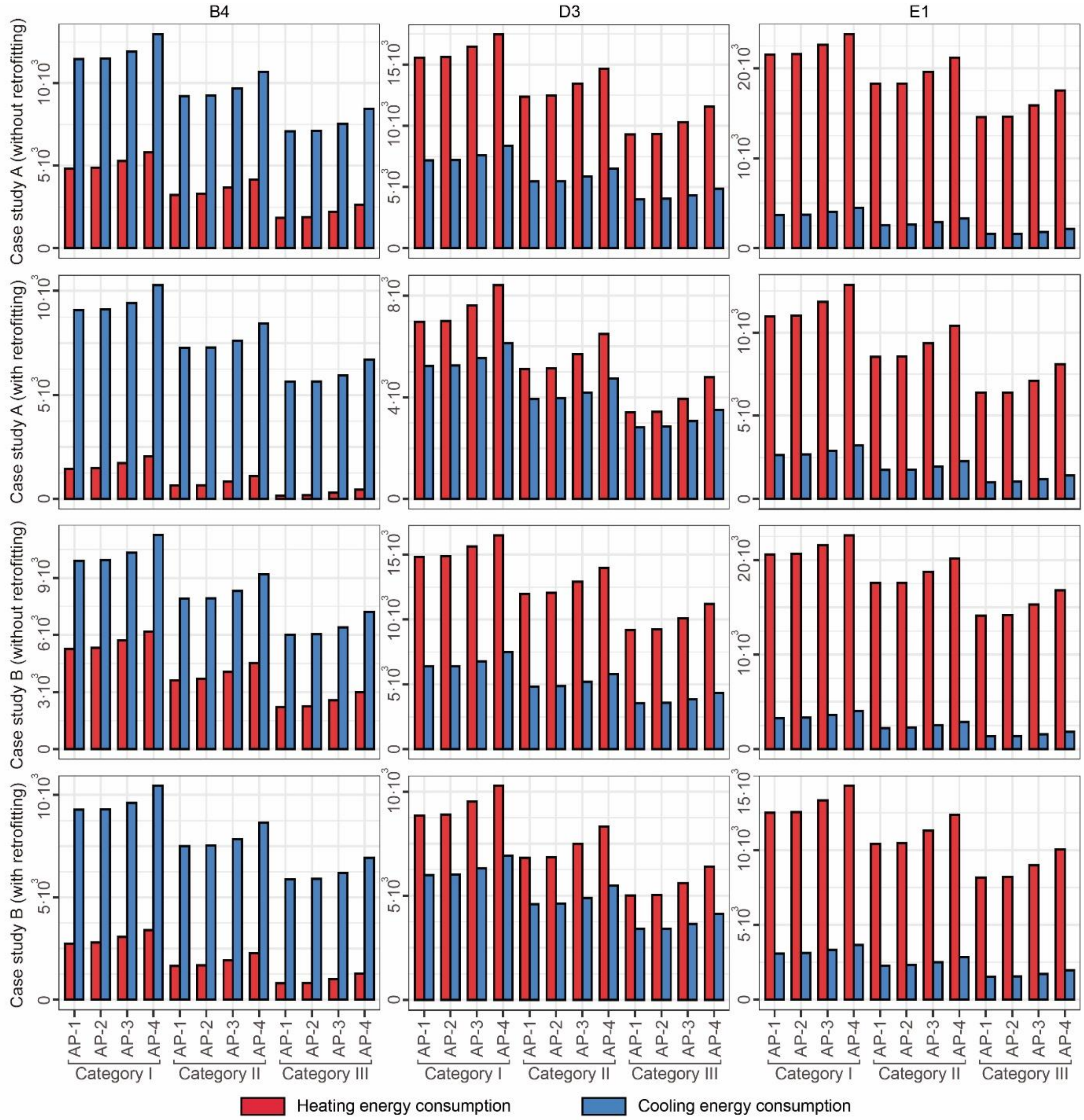

Figure 10. Distribution of the annual energy consumption obtained in the case studies with the approaches of adaptive setpoint temperatures in 2100.

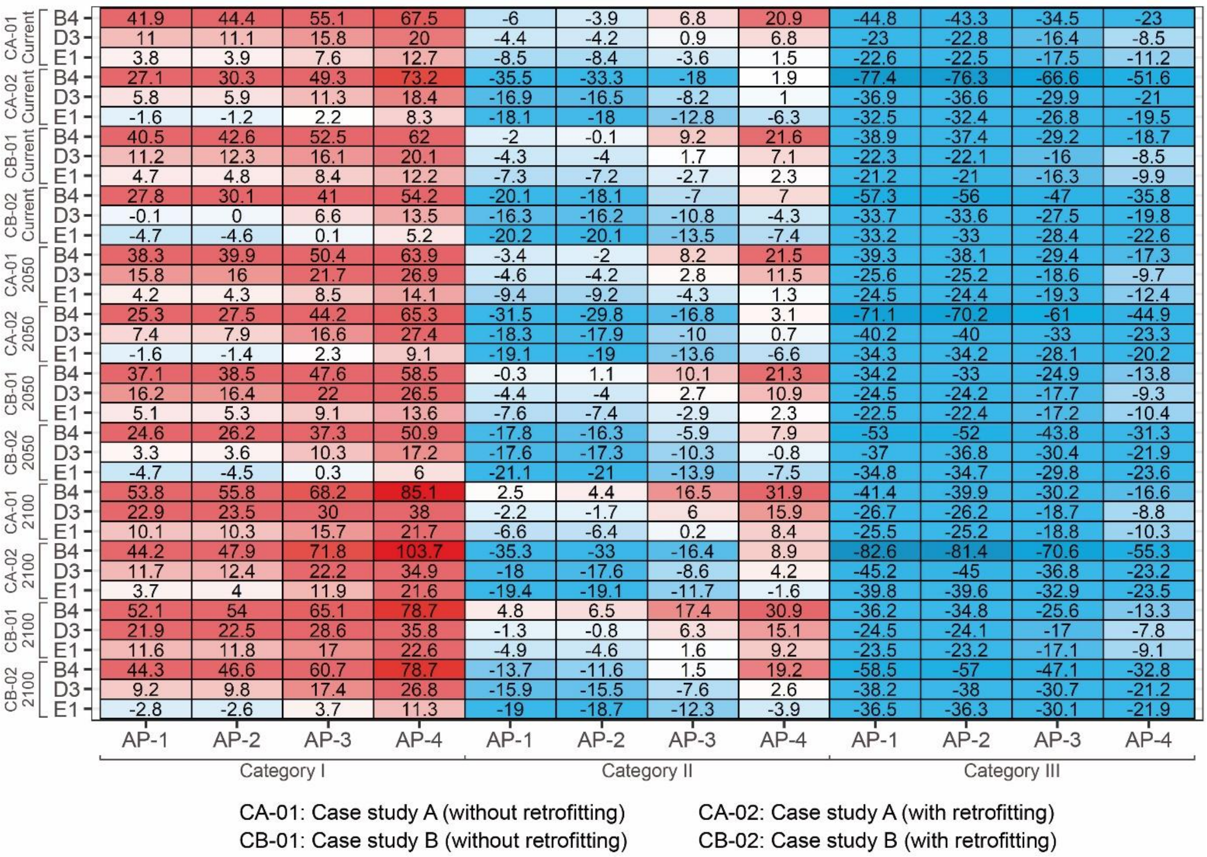

Figure 11. Heatmap with the percentage deviation obtained in the annual heating energy consumption of the adaptive models in comparison with the static model. Positive values correspond to an increase in energy consumption, and negative values correspond to a saving in energy consumption. This figure represents the results for the 3 scenarios (current, 2050, and 2100).

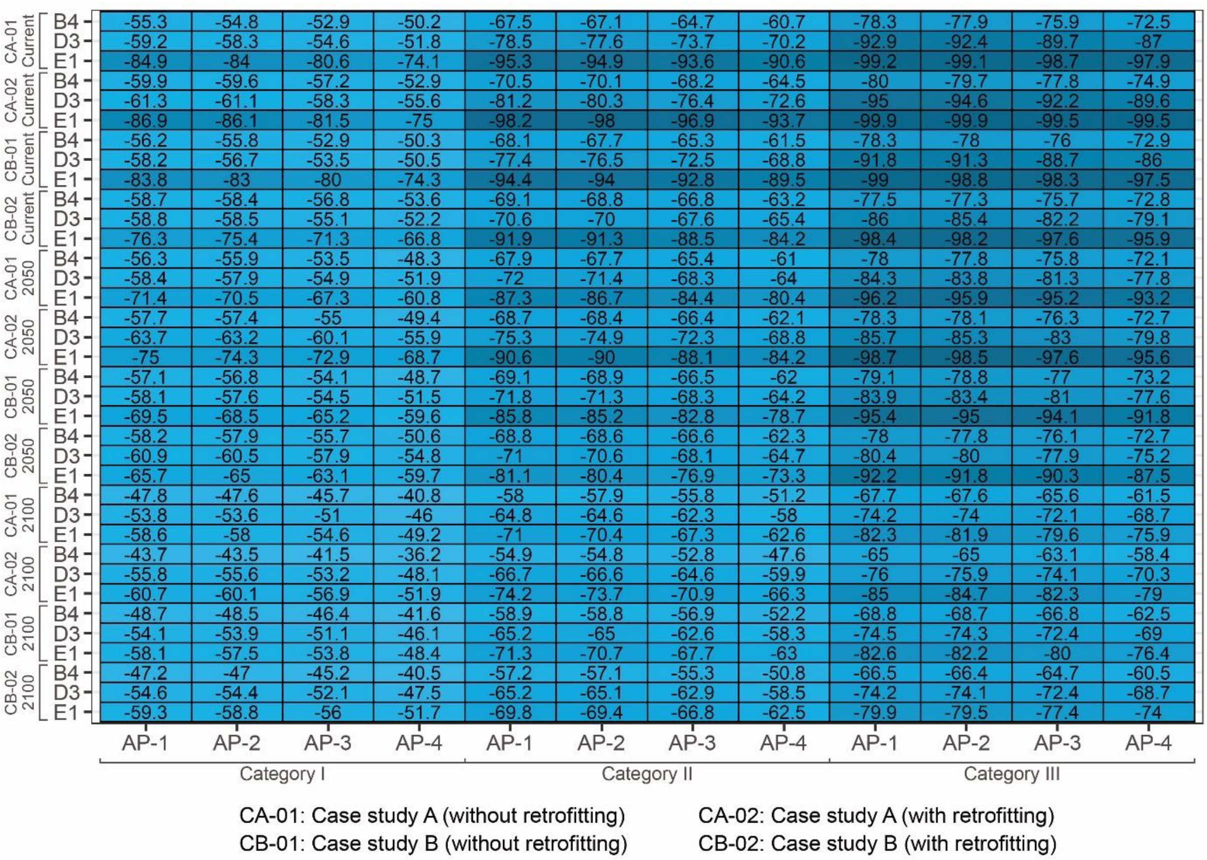

Figure 12. Heatmap with the percentage deviation obtained in the annual cooling energy consumption of the adaptive models in comparison with the static model. Positive values correspond to an increase in energy consumption, and negative values correspond to a saving in energy consumption. This figure represents the results for the 3 scenarios (current, 2050, and 2100).

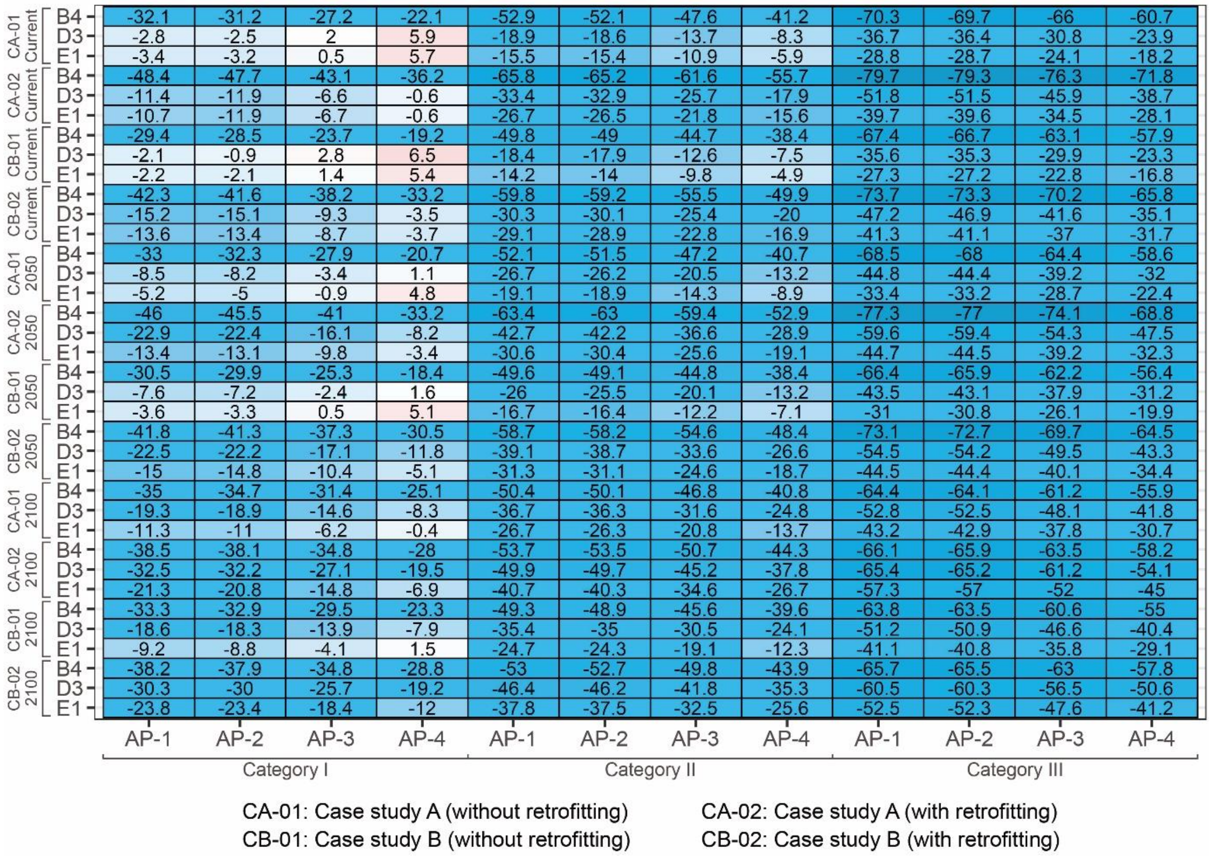

Figure 13. Heatmap with the percentage deviation obtained in the annual energy consumption of the adaptive models in comparison with the static model. Positive values correspond to an increase in energy consumption, and negative values correspond to a saving in energy consumption. This figure represents the results for the 3 scenarios (current, 2050, and 2100).

5. Conclusions

Adaptive thermal comfort models are an appropriate tool to obtain building energy savings. One of the possibilities of applying adaptive thermal comfort models is by using adaptive setpoint temperatures. Most studies have shown significant savings in cooling energy consumption, whereas savings in heating energy consumption are lower. Nonetheless, the tendencies of climate evolution throughout the 21st century, with a greater impact on cooling energy consumption, show the huge potential of applying adaptive setpoint temperatures to achieve a building stock with greater resilience.

However, these studies are based on the direct application of the upper and lower limits of the adaptive thermal comfort models, without considering the limitations of the adaptive setpoint temperatures because of the type of HVAC system in the dwelling. Specifically, the accuracy of the thermostat could significantly influence the effectiveness of measures. For this purpose, 3 typologies of thermostats were analysed according to their accuracy: 0.1, 0.5, and 1 ºC. The thermostats of 0.1 ºC virtually obtained the same results of energy saving as those obtained by directly applying the upper and lower limits of each adaptive thermal comfort model. However, the thermostats of 0.1 ºC are related to new HVAC systems with smart thermostat systems, and the thermostats with an accuracy of 0.5 and 1 ºC correspond to old HVAC systems, the most common in existing buildings. In these cases, there are different tendencies in the limitations to apply adaptive setpoint temperatures. This application mainly depends on the type of energy consumption, the climate zone, and the category from EN 16798-1:2019 which best fit to the users of the dwelling. Based on these three aspects, the application of categories I and II in the heating setpoint temperature is not advisable in thermostats with an accuracy of 0.5 or 1 ºC because of the increase generated in energy consumption in comparison with the static operational patterns, even obtaining increases of up to 103.7%. Consequently, category III from EN 16798-1:2019 is the feasible option to obtain heating energy savings in dwellings with thermostat systems with low accuracy. As for cooling energy consumption, the possibilities of energy saving were greater and less influenced by the type of thermostat. Although the application in thermostats with an accuracy of 0.5 or 1 ºC decreased the cooling energy saving obtained, the energy saving was always greater than 40% (even in the year 2100). This aspect is in accordance with the great effectiveness of the adaptive setpoint temperatures to obtain savings in cooling energy consumption and guarantees the huge potential to apply these strategies in the case studies with old HVAC systems. In addition, the use of these measures would allow energy poverty to be reduced in low-income families that cannot pay building energy renovations. If payments are available to improve the building, replacing the existing HVAC system with another to adjust the thermostat with an accuracy of 0.1 ºC (among other aspects) would be an option of energy saving to obtain energy saving results very similar to those obtained in previous studies on adaptive setpoint temperatures.

To conclude, the results of this study are of great interest to engineers and architects with a more accurate knowledge of the potential of applying adaptive setpoint temperatures in existing buildings. Based on both the type of thermostat and the results, the suitability of applying adaptive setpoint temperatures could be estimated if the adaptation capacity of the users of the case study is known beforehand (i.e., the type of category from EN 16798-1:2019 that could be applied). Thus, a low-carbon building stock would be reached more quickly, and a lower energy poverty risk would be guaranteed for low-income families without financing expensive energy conservation measures. However, there are some limitations. On the one hand, the study was carried out in two residential buildings. Although it is expected that similar results are obtained in buildings for other uses (e.g., offices), future studies should consider the variability that energy savings could present according to the type of building. On the other hand, the use of automation systems would allow this type of measures to be adequately implemented. Thus, future studies could analyse the possibility of using automation systems based on dataloggers that process information and provide an automatic thermostat configuration.

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