Title:

Optimization of energy saving with adaptive setpoint temperatures by calculating the prevailing mean outdoor air temperature.

Authors:

David Bienvenido-Huertas[1], Daniel Sánchez-García[2], Alexis Pérez-Fargallo[3], Carlos Rubio-Bellido*[2]
[1]Department of Graphical Expression and Building Engineering, University of Seville, Seville, Spain
[2]Department of Building Construction II, University of Seville, Seville, Spain
[3]Department of Building Science, University of Bío-Bío, Concepción, Chile
*Author to whom correspondence should be addressed;
Higher Technical School of Building Engineering, Ave. Reina Mercedes 4A, 41012 Seville, Spain
E-Mail: carlosrubio@us.es (C.R.B.); Tel.: +34-686-135-595

Highlights:

- Modification of setpoints in 390 simulations to optimize energy consumption.
- The α-values between 0.4 and 0.6 had the lowest energy consumption.
- The number of previous days varied to optimize heating and cooling consumption.
- A saving between 25.73 and 44.89% of the total energy consumption by using adaptive setpoint temperatures.
- Better performance of the α-value from ASHRAE 55-2017 than that from EN 15251:2007.

Abstract:

Many studies are nowadays focused on the application of energy conservation measures (ECMs) to building sector because of the reductions of both greenhouse gases and energy consumption set by the European Union. Heating, Ventilating and Air Conditioning (HVAC) systems are the main causes of most energy consumption in the existing buildings. One of the methods to reduce energy consumption is the modification of setpoint temperatures adapted to external climate conditions but maintaining acceptable comfort levels. The adaptive comfort model of ASHRAE 55-2017 uses the prevailing mean outdoor temperature, which records temperatures of the previous days weighted by a constant α which depends on weather changes. This paper analyses the possibilities of optimizing building energy saving with setpoint temperatures according to the α-value and the number of previous days considered. A total of 390 simulations were conducted by considering three representative climate zones of Spain. The results showed that the α-values between 0.4 and 0.6 had the lowest energy consumption. The use of a low number of previous days also achieved greater reductions in heating energy consumption, whereas a larger number of days was applied to cooling energy consumption. This study makes progress in using adaptive setpoint temperatures optimally to reduce the energy consumption in the building sector.

Keywords:

Buildings; energy consumption; adaptive setpoint temperatures; prevailing mean outdoor temperature.

1. Introduction

Global warming is leading to a new habitat scenario where there are more and more cases of environmental degradation, increase of ocean levels, and extinction of animals [1]. Consequently, governmental bodies are developing regulations to reduce greenhouse gas (GHG) emissions. The high energy consumption produced by the building sector is among the main causes of energy emissions [2,3]. The deficient energy performance of most building stock influences its high energy consumption [4,5], mainly in countries of Southern Europe as most buildings were designed and built in periods before applying the first standards on energy efficiency [6,7]. The European Union has therefore set the need that all member states reduce the GHG emissions of the building stock by 90% by reducing building energy consumption, but maintaining acceptable internal thermal conditions [8].

Other increasing problems in recent years, such as energy poverty [9,10] and the increase of death rate because of inappropriate internal thermal conditions [11,12], stress the need to improve the building stock performance. In this sense, difficulties to establish limitations when defining the energy poverty are worthy mentioned. Many European countries include different definitions of the concept, whereas other countries (e.g., Spain) does not have any legal definition [13]. An acceptable definition was given by Bouzarovski and Petrova [14] and Li et al. [15] by considering as energy poverty those cases in which families have limitations to access to energy sources or have a deficient access, thus limiting habitability conditions. Another definition was given by Boardman [16], who considered those households presenting limitations to guarantee an acceptable thermal comfort in the interior and expending more than 10% of their income on the energy consumption. The heterogeneities of approaches for the energy poverty is also showed by the existing indicators to quantify it, which have been developed by many research studies: (i) Fabbri [17] developed the Building Fuel Poverty Index, which combines the heating energy consumption of the building and the income average with a threshold of fuel poverty of 6.9%; (ii) Nussbaumer et al. [18]developed the multidimensional energy poverty index, which is based on 5 basic energy services by suing 6 different indicators. A family is at risk if the multidimensional energy poverty index is higher than the predefined threshold value; (iii) Nussbaumer et al.'s multidimensional energy poverty index [18] was modified by Bonatz et al. [19], who developed a new energy poverty index to measure the cases of fuel poverty in Germany and in China. They also introduce indicators of access and affordability to compare countries with different economic development levels; (iv) Wang et al. [20] developed the energy poverty comprehensive evaluation index to be applied in China. This index is obtained by summing four factors: the energy service availability, the energy consumption cleanliness, the energy management completeness, and the household energy affordability and energy efficiency; and (v) Desiere et al. [21] developed the progress out of poverty index, which is based on 10 weighted questions on the characteristics of families. The combination of the values assigned to each question determines the risk of energy poverty.

A common aspect of most approaches of energy poverty is the existing relationship between the internal thermal comfort and the energy consumption required to guarantee it. Energy consumption mainly comes from the use of Heating, Ventilating and Air Conditioning (HVAC) systems [25,26]. Although variations in this type of consumption are maybe due to constructive issues [22], socioeconomic factors can influence the energy consumption of dwellings [23,24]. So, the existing relationship between the building energy demand, behaviour patterns of users and social and economic factors can significantly influence energy consumption. This fact becomes important if the household-scale affect the country-scale [22].The application of energy conservation measures (ECMs) reducing the HVAC system energy consumption would therefore achieve the sustainability goals proposed.

Energy consumption is related to setpoint temperatures, which play an important role in the equilibrium between demand and supply sides [27,28], mainly due to their influence on the HVAC system performance [29]. The use of setpoint temperatures which are appropriate to the environmental characteristics of each area would reduce the building energy consumption without implying a huge economic investment [30]. Several studies analyse the influence of the variation of setpoint temperatures on the building energy saving: (i) Parry et al. [31] analysed the possibilities of reducing the energy consumption of an office building in Zurich. The increase between 2 and 4 ºC in the cooling setpoint temperature reduced the annual energy consumption by one-third; (ii) another study by Wan et al. [32] analysed an office building in Hong Kong. The use of cooling setpoint temperatures greater than 25.5 ºC obtained high energy savings in all climate scenarios (both current and future); and (iii) Spyropoulos and Balaras [33] studied several bank branches in Greece. The use of setpoint temperatures of 20 °C for heating and 26 °C for cooling reduced the total energy consumption by 45%. These research studies were analysed by considering that the thermal comfort models of HVAC systems are based on the Predicted Mean Vote Index (i.e., setpoint temperatures were fixed and did not change with the oscillations of the external temperature). Adaptive thermal comfort models therefore consider human being's thermal adaptability in the face of external climate variations, thus determining setpoints based on adaptive thermal comfort models.

Several studies have analysed the energy saving potential by using setpoint temperatures: (i) Sánchez-Guevara Sánchez et al. [34] analysed 3 block of flats in Avila, Madrid, and Seville with setpoint temperatures monthly varying by using the model of ASHRAE 55-2017 [35]. The results reduced the building energy consumption between 20 and 80%; (ii) Van der Linden et al. [36] analysed the energy saving achieved with the thermal comfort model of ISSO74 [37]. The use of the lower limit of the standard reduced the energy consumption by 74% [38]; (iii) Sánchez-García et al. [28] analysed the reduction of energy consumption in a mixed-mode office building in Seville. The use of daily adaptive setpoint temperatures obtained savings between 36.7 and 59.5% of the building energy consumption; and (iv) recently, Sánchez-García et al. [39] analysed the application of adaptive setpoint temperatures in a residential building. The analysis was performed in 3 cities: Avila, Madrid, and Seville. The energy consumption was saved between 10 and 46% according to the type of climate in which the building was located. The real possibilities application of these models have also been analysed in several studies: (i) Aparicio-Ruiz et al. [40] applied an adaptive comfort algorithm to a real mixed-mode building and showed the real possibilities of applying the models by implementing them in the building automation system; and (ii) Bienvenido-Huertas et al. [41] analysed the possibilities of using weather stations to determine adaptive setpoint temperatures, with the result of estimating setpoint temperatures suitably even with weather stations located far from the building. In addition, the use of adaptive comfort models can imply that a building operates in free-running during many hours, thus exceeding 90% with acceptable building standards, even in cold climates [42].

It is important to highlight the possibilities suggested by the ECM in comparison with others traditionally applied, such as the improvement of insulation of the envelope or of HVAC systems. This is due to the rebound effects produced by these performances. Rebound effects are understood as those new expenditures made by users due to the saving achieved in the energy bill of households [43,44]. The effects should be taken into account because the energy savings achieved by certain performances can be removed [45]. For example, an indirect effect could be the possibility that users use the economic saving achieved to increase internal thermal comfort levels (e.g., increasing the setpoint temperatures for heating) [46]. If adaptive setpoint temperatures were used, then the rebound effect would be limited. Moreover, the ECM constitutes an opportunity for households with low incomes to reduce their energy consumption due to the existing economic limitations with other ECMs [47]. There would therefore be a greater possibility that families escape from cases of energy poverty and internal thermal comfort conditions would be improved.

The most used adaptive thermal comfort models are in EN 15251:2007 [49] (recently modified in EN 16798-1:2019 [50]) and ASHRAE 55-2017 [35]. ASHRAE 55-2017 sets two thermal comfort categories according to the users' percentage of acceptability: 80 and 90%. The standard does not limit the use of each category according to the building typology [51]. The models therefore establish the lower and upper limits for the internal operative temperature of any building. Limits are determined with the prevailing mean outdoor air temperature ($\overline{t_{pma(out)}}$), which is in turn determined through the variations of the external temperature of the previous days (see Eq. (1)). The temperature is equivalent to the running mean outdoor temperature included in EN 16798-1:2019, whose formulation is the same. Through $\overline{t_{pma(out)}}$, lower and upper limits for acceptability percentages of 80 and 90% can be obtained (see Eqs. (2)-(5)).

$$\overline{t_{pma(out)}} = (1-\alpha)\cdot\sum_{d=1}^{n}\left(\alpha^{(i-1)}\cdot T_{ext,d}\right) \quad [ºC] \tag{1}$$

$$Upper\ limit\ (80\%\ acceptability) = 0.31\cdot\overline{t_{pma(out)}} + 21.3 \quad [ºC] \tag{2}$$

$$Lower\ limit\ (80\%\ acceptability) = 0.31\cdot\overline{t_{pma(out)}} + 14.3 \quad [ºC] \tag{3}$$

$$Upper\ limit\ (90\%\ acceptability) = 0.31\cdot\overline{t_{pma(out)}} + 20.3 \quad [ºC] \tag{4}$$

$$Lower\ limit\ (90\%\ acceptability) = 0.31\cdot\overline{t_{pma(out)}} + 15.3 \quad [ºC] \tag{5}$$

Where α is a value dependent on the location of the building and whose value oscillates between 0 and 1, n is the number of previous days which should be at least 7 and without a maximum limit of days, and $T_{ext,d}$ is the daily external average temperature of the previous day d [ºC].

The importance of $\overline{t_{pma(out)}}$ to apply adaptive models should be stressed. First, ASHRAE 55-2017 set that $\overline{t_{pma(out)}}$ should be between 10 and 33.5 ºC to apply adaptive models. So, $\overline{t_{pma(out)}}$ determines when adaptive models can be used. Second, the calculation of $\overline{t_{pma(out)}}$ depends on two parameters: the α-value and the number of previous days used in the calculation. Although not very accurate, ASHRAE 55-2017 gives some recommendations for the calculation: (i) for the α-value, the use of a value of 0.9 for climates with a high synoptic-scale weather variability (e.g., tropical climates) is recommended, as well as a value of 0.6 for climates with a low synoptic-scale weather variability (e.g., middle latitudes); and (ii) for the number of days, the only recommendation is that it should be at least 7 days, without specifying the maximum.

In the existing research works on the use of adaptive models, an α-value of 0.8 and the number of 7 days have always been used [28,34,39–41] in accordance with what is set in EN 15251:2007 [49]. However, ASHRAE 55-2017 recommends another value for latitudes of countries where EN 15251:2007 would be applied (i.e., the countries of Europe). A weakness is therefore found in the application of adaptive models. For this reason, this study analyses the possibilities of optimizing the building energy saving by using adaptive setpoint temperatures. The various possibilities of determining adaptive setpoint temperatures according to $\overline{t_{pma(out)}}$ and the energy saving associated are analysed. The possibilities of $\overline{t_{pma(out)}}$ are according to the α-value and the number of previous days considered. The analyses were performed in a representative case study of the building stock in Spain located in the 3 cities which were previously analysed [34,39]: Avila, Madrid, and Seville. The aim was to assess the possibilities of adapting the ECM to various climates, as recommended by other ECMs [52,53]. The results were obtained through a simulation process made up of 390 various simulations.

This paper is structured by starting with the methodology in Section 2, which describes the case study analysed, the climate zones considered, and the different configurations of the adaptive models. Section 3 discusses the results by distinguishing between the effect of the calculation of $\overline{t_{pma(out)}}$ and the energy saving achieved with respect to the current state of the case study. Finally, Section 4 summarizes the main conclusions.

2. Methodology

2.1. Case study and thermal model

The case study is a building from 1978 and anterior to the NBE-CT 79 standard [54], so it was designed without insulating material as the standard established the need of using insulating material in building envelopes [55]. Two aspects stressing the importance of the case study are as follows: (i) 56.35% of the building stock in Spain was built before the NBE-CT 79 [56]; and (ii) the design of the building floor analysed is similar to the typologies of linear block of flats, which is the type of construction most built in the period after the Spanish Civil War [57]. This case study is therefore representative of most building stock in Spain, and the results obtained are extrapolated to most buildings in Spain with a deficient energy performance.

The building is made up of 8 floors (see Figure 1). The dwelling has 3 bedrooms, 1 kitchen, 1 bath, and 1 living room, with a surface area of 77 m^2 and facing north-west, south-east, and south-west. The envelope is designed according to the designs used in the building period, which are characterized by a double-leaf brick with air gap [58,59]. The layers of the envelope and the thermophysical properties of the different materials were determined with the methodology by Ficco et al. [60]. Table 1 includes the layers and the thermophysical properties of the envelope elements. The case study has a heat pump with a Coefficient of Performance (COP) of 2.10, and an Energy Efficiency Ratio (EER) of 2.00.

Table 1. Technical characteristics and thermophysical properties of the case study.

Component	Description	Thickness [m]	U-Value [W/(m²K)]	Internal Heat Capacity [kJ/(m²K)]
External wall	Cement plaster Hollow brick Air gap Cement plaster Brick facing	0.26	1.35	80.35
Internal wall	Cement plaster Double hollow brick masonry Cement plaster	0.10	2.74	39.00
Windows	Aluminum frame; simple glazing 3 mm	-	5.89	-
Floor and paving	Terrazzo paving Sand Lightweight floor slab, cast in place, with a depth of 25 cm	0.28	1.76	147.63

Based on the data compiled of the building, a thermal model was created in DesignBuilder (see Figure 1 (a)) and validated following the criteria and the limit values set in the ASHRAE Guideline 14-2014 [61], which indicates that the monitoring of variables and the analysis of the Mean Bias Error (MBE) (Eq. (6)) and the Coefficient of Variation of the Root Mean Square Error (CV(RMSE)) (Eq. (7)) between the simulated and measured values determines the reliability of the thermal model [62]. It is established as limit conditions for hourly values that MBE oscillates between -10 and 10% and that CV(RMSE) is lower than 30%. To validate the model, both the indoor air temperature of rooms 1 and 2 and the outdoor dry-bulb temperature were monitored. A total of 3 different monitorings were conducted throughout the year: test 1 (T 1) between Jan 14th and Feb 03rd, test 2 (T 2) between May 14th and Jun 12th, and test 3 (T 3) between June 22nd and Jul 22nd. Figure 1 (c) and (d) show that the values obtained both in MBE and CV(RMSE) were lower than the limit values set by the ASHRAE Guideline 14-2014, thus ensuring the validity of the thermal model.

$$MBE = \frac{\sum_{i=1}^{n}(y_i - x_i)}{n} \cdot 100 \quad [\%] \tag{6}$$

$$CV(RMSE) = \frac{1}{\bar{y}}\left(\frac{\sum_{i=1}^{n}(y_i - x_i)^2}{n}\right)^{1/2} \cdot 100 \quad [\%] \tag{7}$$

Where y_i is the measured value, x_i is the simulated value, n is the number of measures, and $\bar{y}$ is the average of measured values.

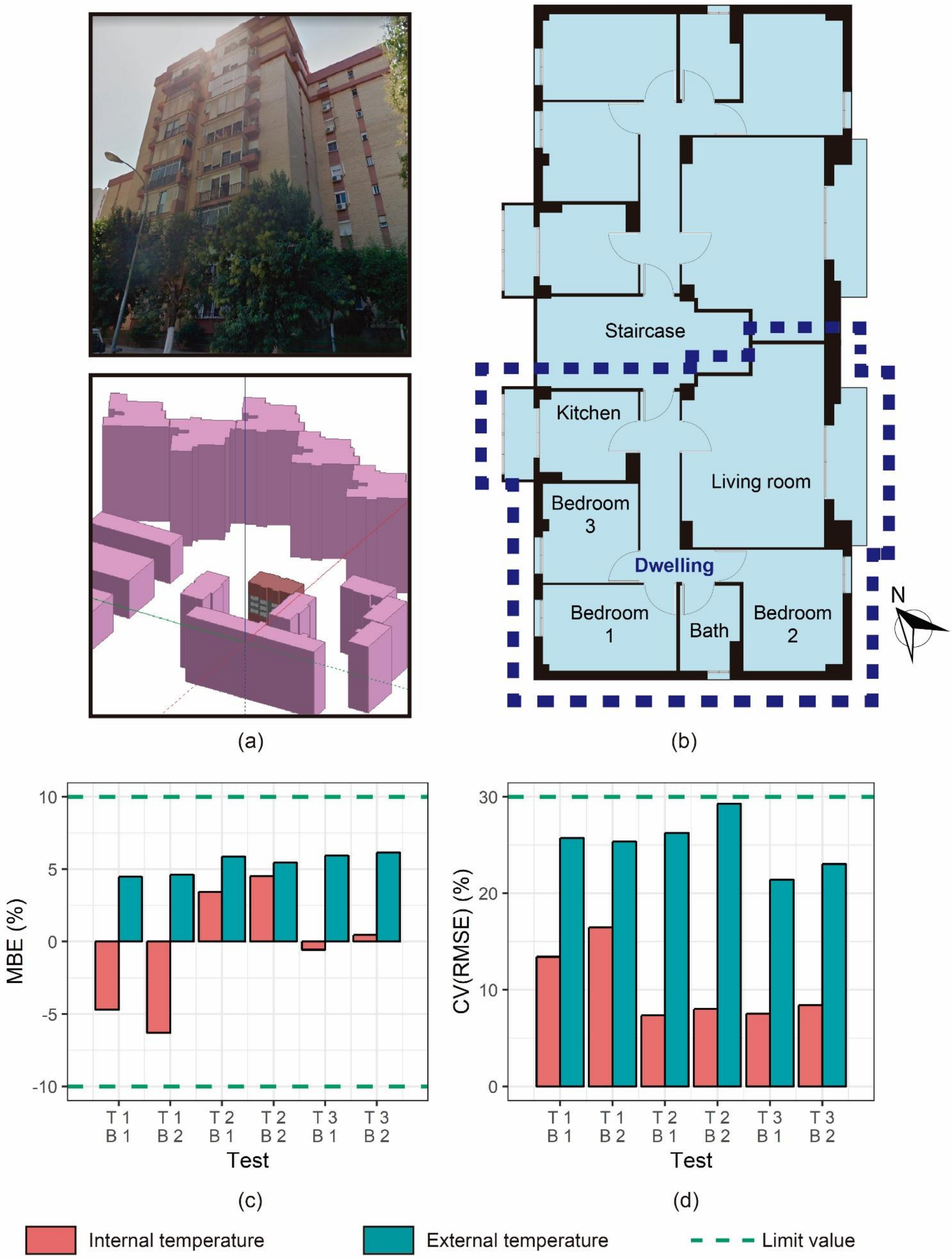

Figure 1. Case study: (a) photograph of the building and the thermal model; (b) dwelling distribution; (c) values of MBE in the validation of the thermal model; and (d) values of CV(RMSE) in the validation of the thermal model. B 1 is Bedroom 1 and B 2 is Bedroom 2.

As usage profiles of the case study, the profile defined in the Spanish Building Technical Code [63] was used (see Figure 2). According to this building code, the dwelling occupation varies according to the day analysed: as for working days, the occupation varies from 25 to 100%, whereas for weekends, the occupation is 100%. The load of both equipment and lighting devices has the same usage profiles, which varies according to the hour of the day. Values of 100% for different loads according to the code are as follows: the latent load is 1.36 W/m^2, the sensible load is 2.15 W/m^2, and the load both for equipment and lighting devices is 4.40 W/m^2.

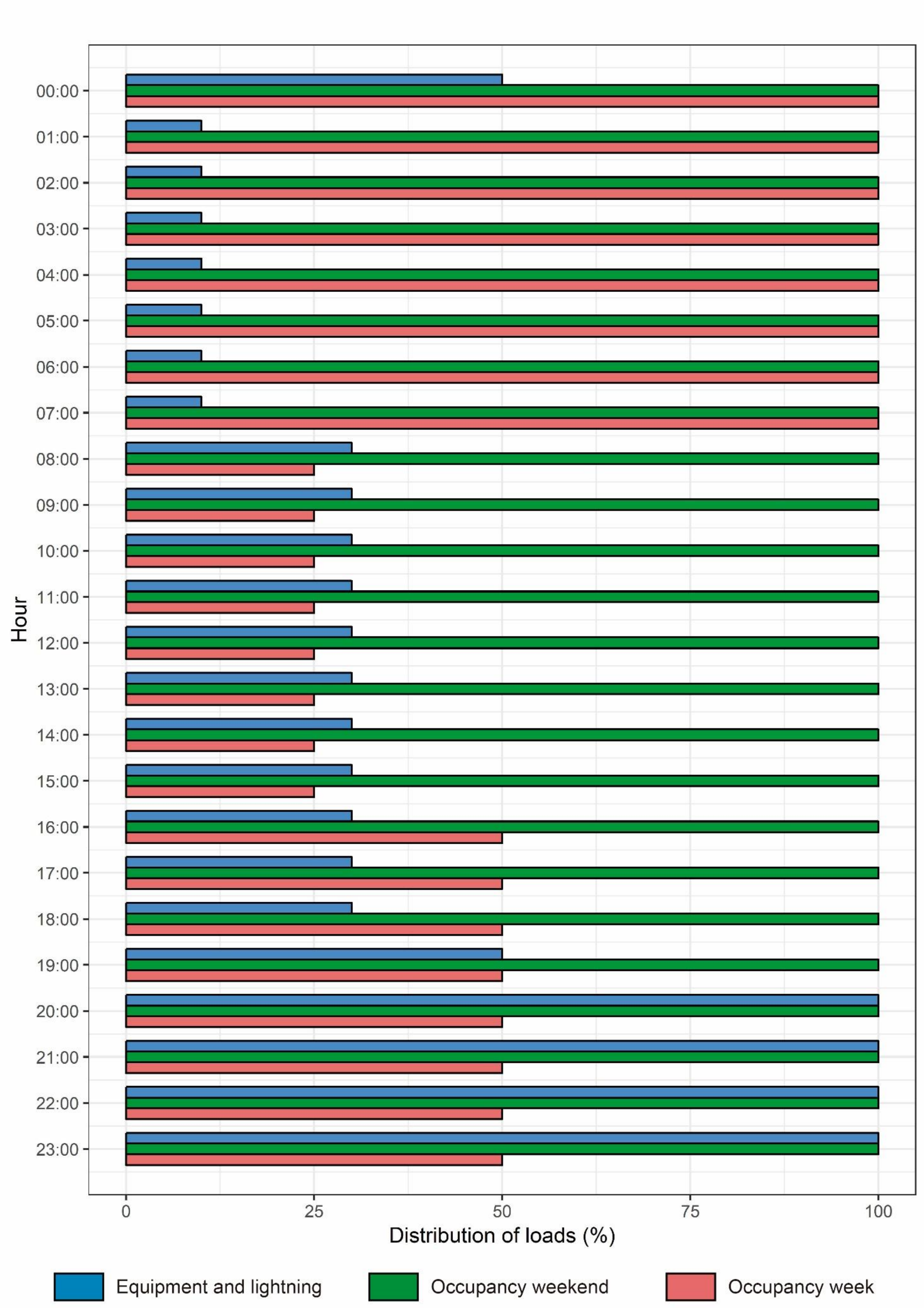

Figure 2. Usage profile of the dwelling according to the Spanish Building Technical Code.

The operation of the HVAC system of the building was configured according to the Spanish Building Technical Code. Table 2 includes the operation of HVAC systems according to the building code. As can be seen, the code recommends using static setpoint temperatures throughout the year. The results obtained with the model were used as results of the current state of the building, and Section 3 refers to the model by using the "static" term.

Table 2. Schedule of the setpoint temperatures used in the static model.

Setpoint temperature	Static setpoint temperature [ºC]								
	January - May			June - September			October - December		
	00:00-7:00	08:00-15:00	16:00-23:00	00:00-7:00	08:00-15:00	16:00-23:00	00:00-7:00	08:00-15:00	16:00-23:00
Cooling	-	-	-	27	-	25	-	-	-
Heating	17	20	20	-	-	-	17	20	20

As mentioned previously, this study aims at analysing the $\overline{t_{pma(out)}}$ in the calculation of the adaptive setpoint temperatures to optimize the energy saving achieved in the building. For this purpose, the category of acceptability of 80% from ASHRAE 55-2017 was used. The standard has an international nature because of its development through 160 case studies located in countries all over the world, so its possibility of application in the cities analysed was ensured. Also, it sets a series of determinants for its application: (i) the internal space should be equipped with windows to be opened and adjusted by the occupants; (ii) mechanical ventilation systems without a cooling system can be used, but it is permissible that the space has a heating system (although the model cannot be applied in use); (iii) occupants should have an almost sedentary physical activity, with metabolic rates between 1.0 and 1.3 met; (iv) the occupants should freely adapt their clothing to the internal and/or external thermal conditions between values of 0.5 and 1.0 clo. It is imperative to consider that this paper does not consist of a strict application of the standard, as the use of air conditioning is not allowed. However, adaptive comfort limits are used as setpoint temperatures. This aspect is in accordance with recent research studies on the issue which are analysed in Section 1. The category of acceptability of 80% was used according to that recommended in ASHRAE 55-2017, which stresses the difficulty of obtaining an acceptability of 90% in actual buildings [35]. Limit values of 80% were therefore used to define cooling (upper limit) and heating (lower limit) adaptive setpoint temperatures. The standard sets that the comfort model is applicable when $\overline{t_{pma(out)}}$ is within the range between 10 and 33 ºC, and it is not applicable otherwise, so there is not an adaptive comfort limit, and consequently it is not possible to determine an adaptive setpoint temperature (i.e., the behaviour of the setpoint temperature is static). For this study, and similarly to other existing research works on this issue [27,28,39], upper and lower limits were horizontally extended in the extremes of application of the model of ASHRAE 55-2017 with the aim of using setpoint temperatures based on the adaptive comfort model when the model was not applicable. In addition, to make representative comparisons between the static and the adaptive model, the usage profile of the HVAC system was similarly adapted as set in the Spanish Building Technical Code but using adaptive setpoint temperatures (see Table 3).

Table 3. Schedule of the setpoint temperatures used in the adaptive model.

Setpoint temperature	Range	Adaptive setpoint temperature [ºC]								
		January - May			June - September			October - December		
		00:00-7:00	08:00-15:00	16:00-23:00	00:00-7:00	08:00-15:00	16:00-23:00	00:00-7:00	08:00-15:00	16:00-23:00
Cooling	$\overline{t_{pma(out)}} < 10$ °C	-	-	-	24.4	-	24.4	-	-	-
	10 °C ≤ $\overline{t_{pma(out)}} \leq 33.5$ °C	-	-	-	Eq. (2)	-	Eq. (2)	-	-	-
	$\overline{t_{pma(out)}} > 33.5$ °C	-	-	-	31.69	-	31.69	-	-	-
Heating	$\overline{t_{pma(out)}} < 10$ °C	17.4	17.4	17.4	-	-	-	17.4	17.4	17.4
	10 °C ≤ $\overline{t_{pma(out)}} \leq 33.5$ °C	Eq. (3)	Eq. (3)	Eq. (3)	-	-	-	Eq. (3)	Eq. (3)	Eq. (3)
	$\overline{t_{pma(out)}} > 33.5$ °C	24.69	24.69	24.69	-	-	-	24.69	24.69	24.69

As mentioned earlier, there are two parameters in the calculation of $\overline{t_{pma(out)}}$ influencing its determination: the α-value and the number of previous days used. Various combinations were also analysed in the calculation of $\overline{t_{pma(out)}}$, thus constituting each combination a different adaptive model. The values used in each parameter were as follows: the α-value oscillated between 0.4 and 0.9 and the number of previous days oscillated between 7 and the maximum number acceptable for each α-value. The calculation procedure of $\overline{t_{pma(out)}}$ is through a weighted sum, so the inverse of (1- α) determines the maximum number of days because the sum of α^x should be the same as the inverse of (1- α). As a result, the maximum number of days is 8 for values of 0.4, whereas the number is 74 for 0.9. Table 4 indicates the various combinations analysed. A total of 130 different simulations of adaptive models were analysed and compared to the simulation of the static model in each location of the model analysed. As Subsection 4.2. indicates, 3 climate zones were analysed. A total of 130 simulations were made in each climate zone, so the results obtained in this study are based on a total of 390 simulations.

Table 4. Combinations of α-values and the number of days.

α-value	Range of days
0.4	7-8
0.5	7-11
0.6	7-15
0.7	7-22
0.8	7-35
0.9	7-74

2.2. Climate zones

The use of adaptive models depends on external climate conditions, so the influence of $\overline{t_{pma(out)}}$ was analysed in 3 climate zones with clearly different characteristics. For this purpose, a total of 3 cities with different climate differences were selected, each corresponding to a climate zone: Avila, Madrid, and Seville (see Table 5). These cities were also used because they were used in other research studies associated with the use of adaptive setpoint temperatures [34,39]. The climate differences among them can be found in several climate classifications. On the one hand, the Köppen-Geiger classification [64] groups them in 3 different groups: Avila corresponds to the Csb class (continental Mediterranean climate with mild summers and cold winters), Madrid corresponds to the Bsh class (semiarid cold climate with moderate cold winters and hot summers); and Seville corresponds to the Csa class (Mediterranean climate with mild winters and dry and very hot summers). On the other hand, cities present different classifications according to the Spanish Building Technical Code, in which 12 climate zones are distinguished according to the level of winter and summer climate severity. For the winter climate severity, a letter between A (not very severe) and E (very severe) is assigned, whereas for summer climate severity, a number between 1 (not very severe) and 4 (very severe) is used. Among the possible combinations, climate classifications are obtained in the 3 cities and, like in the Köppen-Geiger's classification, they have different characteristics: E1 in Avila, D3 in Madrid, and B4 in Seville. Moreover, these differences are showed in the values obtained for heating degree day (HDD) and for cooling degree day (CDD) (see Table 5).

Table 5. Cities selected for the study.

City	Latitude	Length	Height	Climate zone (Köppen-Geiger)	Climate zone (Spanish Building Technical Code)	HDD [ºC]	CDD [ºC]
Avila	40.654347	-4.696222	1131	Csb	E1	3,397.30	2.50
Madrid	40	-3.691944	657	Bsh	D3	2,262.20	163.80
Seville	37.383333	-5.98333	11	Csa	B4	1,134.60	369.00

Climate data of the 3 cities were obtained with METEONORM [65]. METEONORM is a software constituted by a database of climate files of 8,325 weather stations which determines hourly climate values in any geographical location by means of interpolations. By using METEONORM, the external temperature values of the 3 cities were obtained for the calculation of $\overline{t_{pma(out)}}$ (see Figure 3), as well as the .epw files used in the simulations.

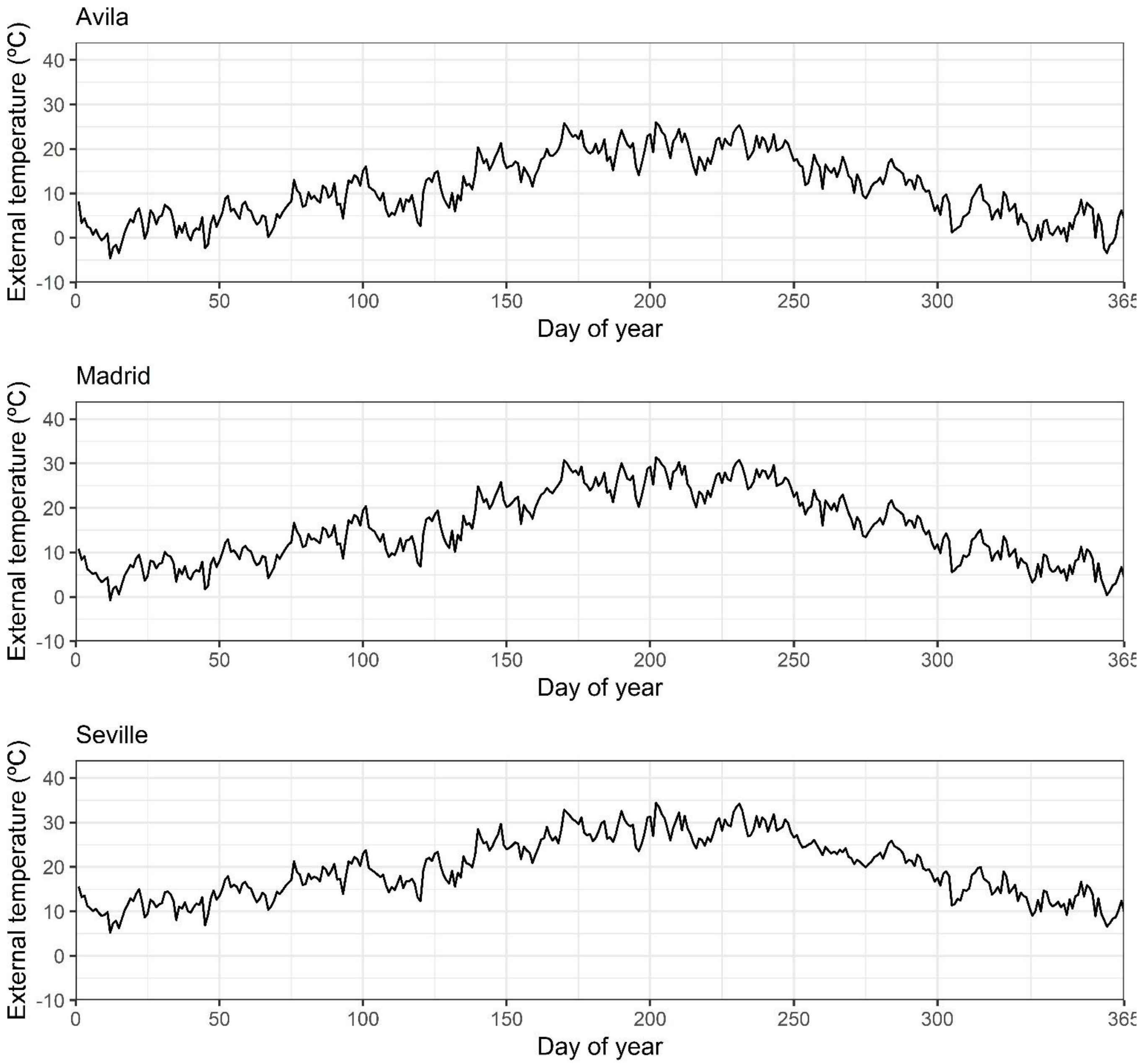

Figure 3. Time series of the external temperature in the 3 cities analysed.

3. Results and discussion

3.1. Analysis of the prevailing mean outdoor temperature

The adaptive setpoint temperatures were optimized by analysing, firstly, the variations of $\overline{t_{pma(out)}}$ according to the parameters required for its calculation to analyse the configuration with the greatest energy saving. As noted earlier, lower and upper limits for the category of 80% of ASHRAE 55-2017 depend on $\overline{t_{pma(out)}}$. The optimal use of $\overline{t_{pma(out)}}$ will therefore increase the energy saving achieved by using this adaptive energy saving strategy.

First, the variations of $\overline{t_{pma(out)}}$ in the 3 cities were analysed. To simplify this part of the results, the results obtained in the number of days when each α-value was stabilized were discussed. Figure 4 shows that the variation of the α-value caused important variations in $\overline{t_{pma(out)}}$ in the 3 cities. The increase of the α-value generated a greater variation of $\overline{t_{pma(out)}}$ with respect to the low values of α-value (see Table 6). So, the average deviation of degrees of the α-value with respect to the $\overline{t_{pma(out)}}$ obtained with 0.4 were greater in the coldest zones (i.e., Avila and Madrid).

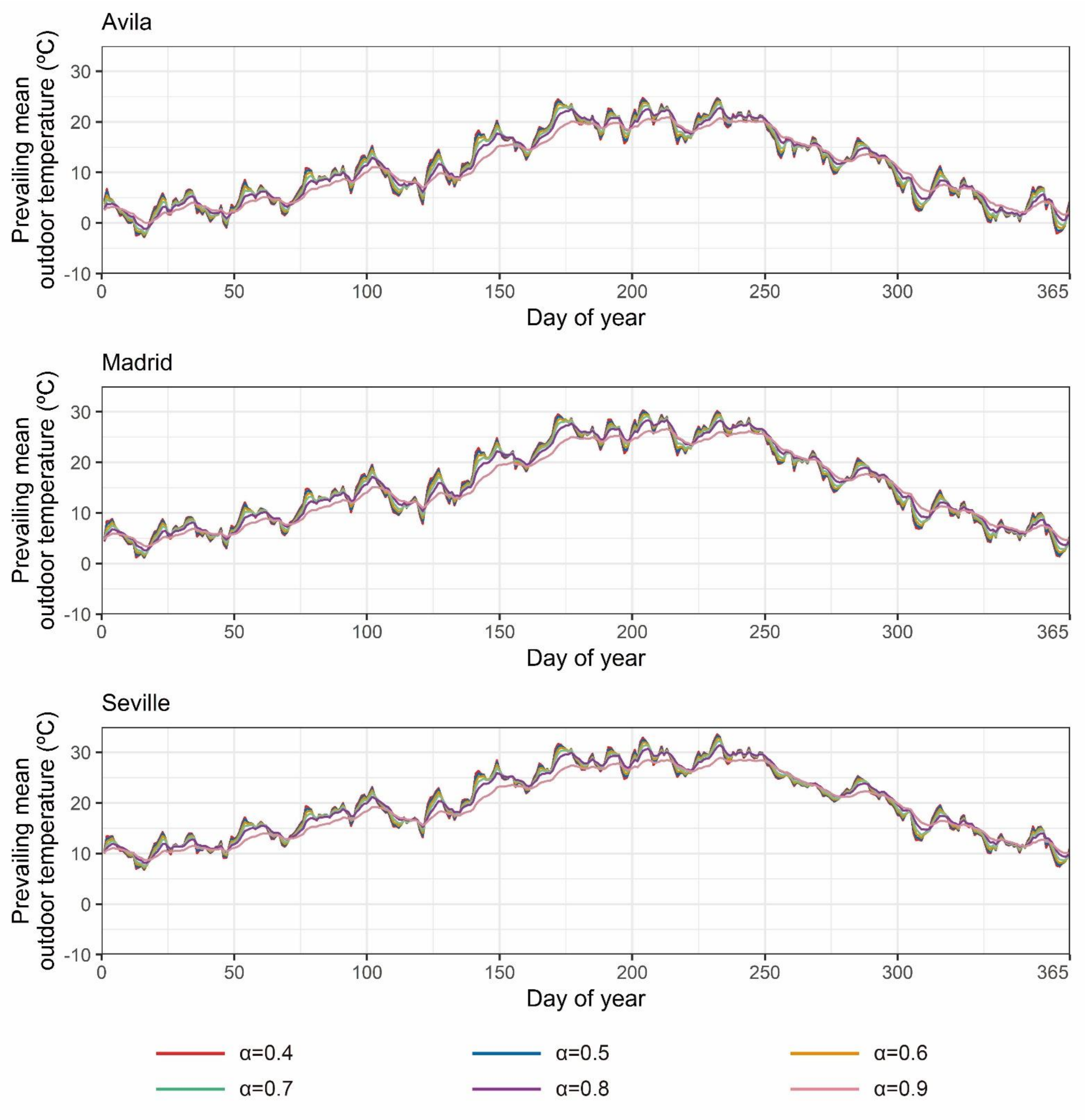

Figure 4. Variation of the prevailing mean outdoor temperature according to the α-value in the various cities.

Table 6. The average deviation of degrees in the calculation of $\overline{t_{pma(out)}}$ between 0.4 and the remaining α-values.

City	α-value	Average deviation of degrees [ºC]
Avila	0.5	0.24
	0.6	0.52
	0.7	0.86
	0.8	1.29
	0.9	1.90
Madrid	0.5	0.23
	0.6	0.49
	0.7	0.81
	0.8	1.23
	0.9	1.87
Seville	0.5	0.20
	0.6	0.43
	0.7	0.72
	0.8	1.09
	0.9	1.69

The variations of $\overline{t_{pma(out)}}$ directly influenced the total energy consumption. As indicated above, there are two important parameters in the calculation of $\overline{t_{pma(out)}}$: the α-value and the number of days used in the calculation. For this reason, the variation presented by the total building energy consumption in the 3 cities was analysed due to the various possibilities of combination in the calculation of $\overline{t_{pma(out)}}$. Figures 5, 6 and 7 represent the results obtained in this process. The influence of the number of days included in the calculation of $\overline{t_{pma(out)}}$ depended on the α-value used. In this sense, a low number of days was used for low values of α-value to achieve the stabilization of building energy consumption values. For α-values equal or higher than 0.7, the number of days was higher. After achieving the stabilization of the $\overline{t_{pma(out)}}$ for the different α-values, the increase of the number of days did not modify the results. Also, it was found that the increase of the number of days influenced heating and cooling energy consumption differently (see Table 7): the heating energy consumption increased as the number of days increased, but the cooling energy consumption decreased. The reason was that $\overline{t_{pma(out)}}$ increased as the number of days of the sum increased, thus leading to an increase of heating and cooling setpoint temperatures. The increase of the heating setpoint temperature was related to an increase of the heating energy consumption, whereas the increase of the cooling setpoint temperature was related to a decrease of the cooling energy consumption. These aspects explain the differences of both types of consumption due to the variation of the number of days. This analysis draws the conclusion that the use of a low number of days of heating setpoint temperatures would obtain greater energy consumption savings, whereas a high number of days would be used for cooling setpoint temperatures. As for the effect of the α-value in the behaviour of the energy consumption obtained in the cities, differences in the curve behaviour of the annual energy consumption were not found between Madrid and Seville, whereas there were differences in the heating energy consumption in Avila. The reason was that the α-values of 0.4 and 0.5 had higher setpoint temperatures than the α-values of 0.6 and 0.7, so the thermal gradient was greater between the internal and the external temperature.

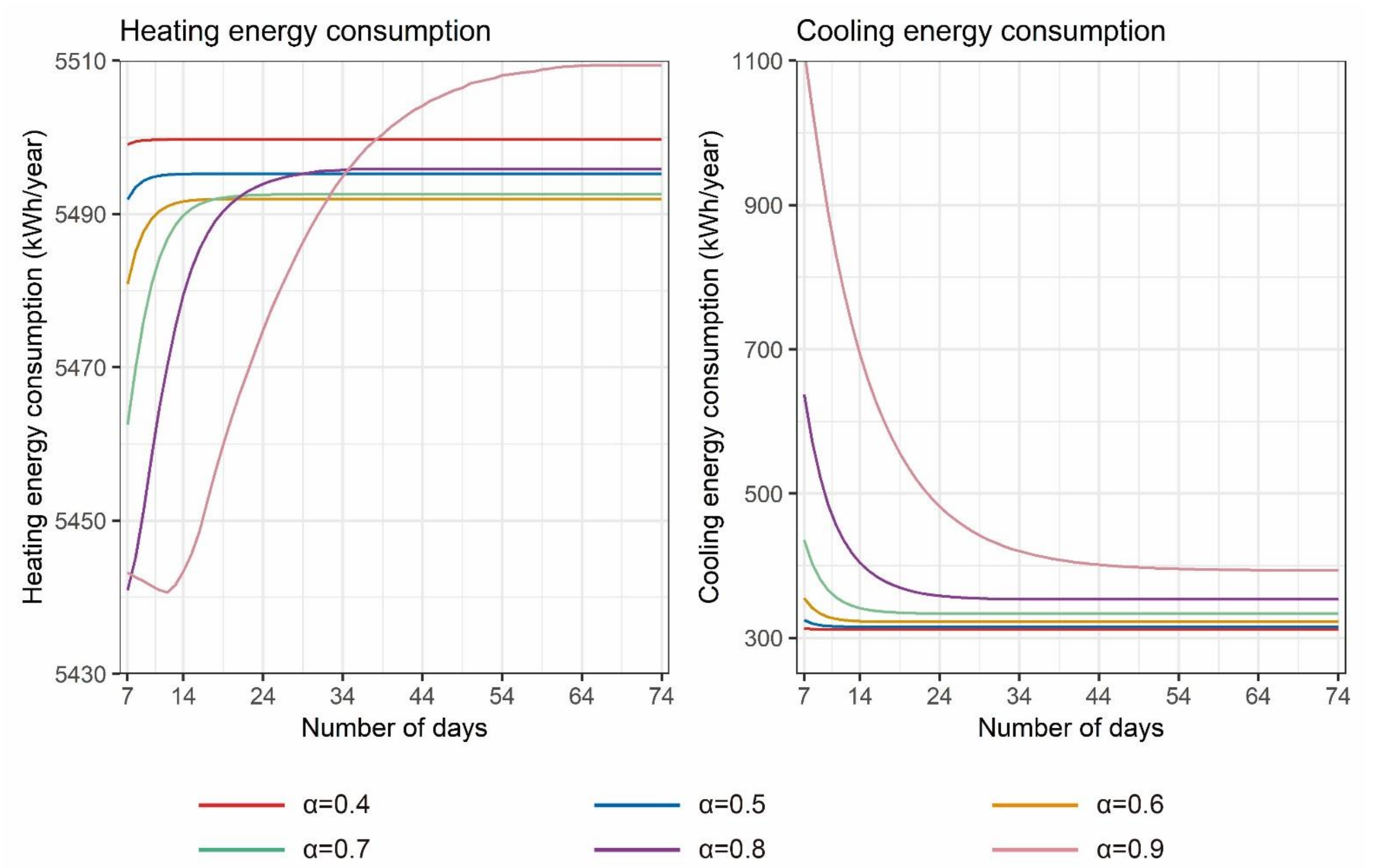

Figure 5. Variation of the energy consumption of the case study in Avila according to the α-value and the number of days used in the calculation of the prevailing mean outdoor temperature.

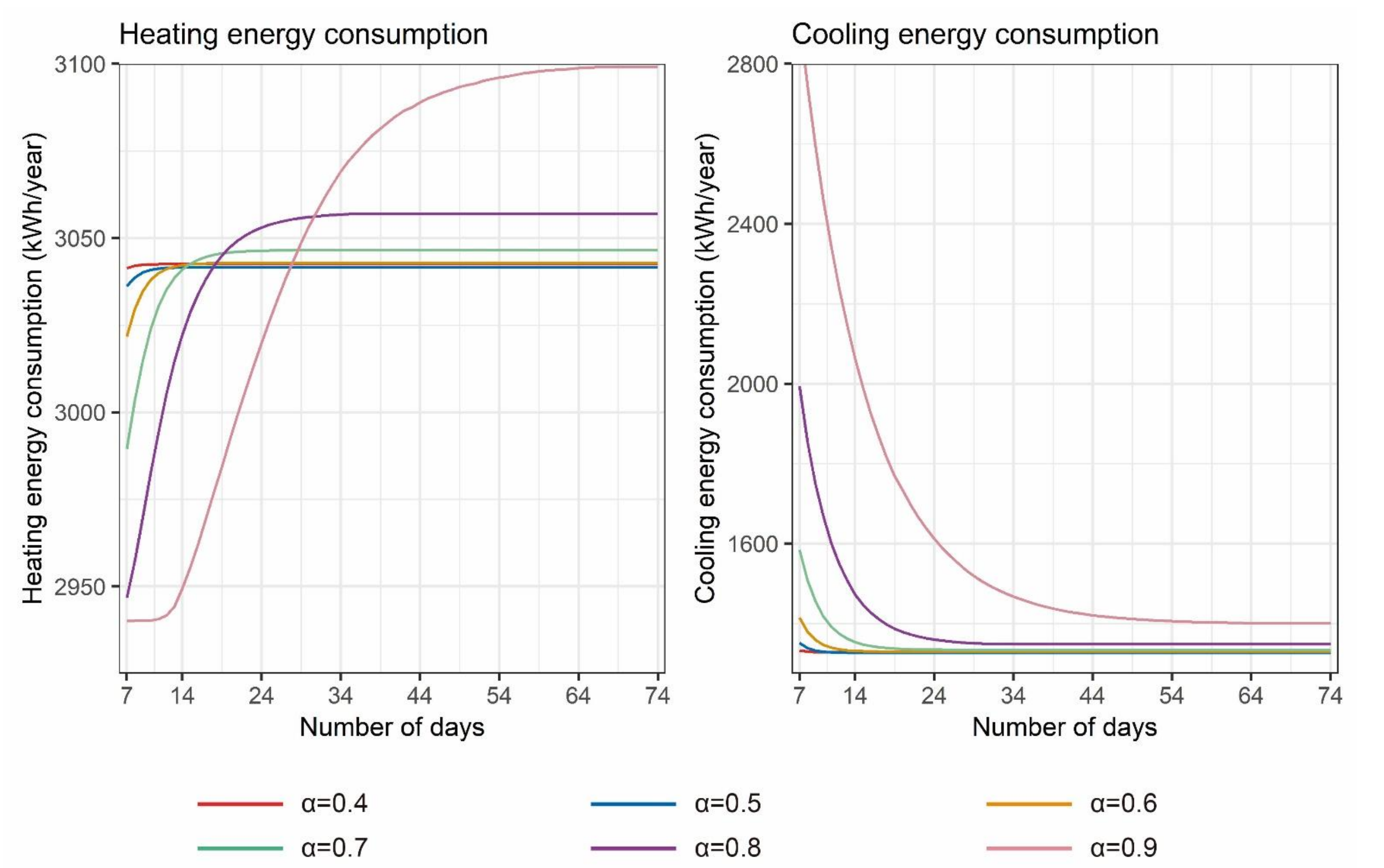

Figure 6. Variation of the energy consumption of the case study in Madrid according to the α-value and the number of days used in the calculation of the prevailing mean outdoor temperature.

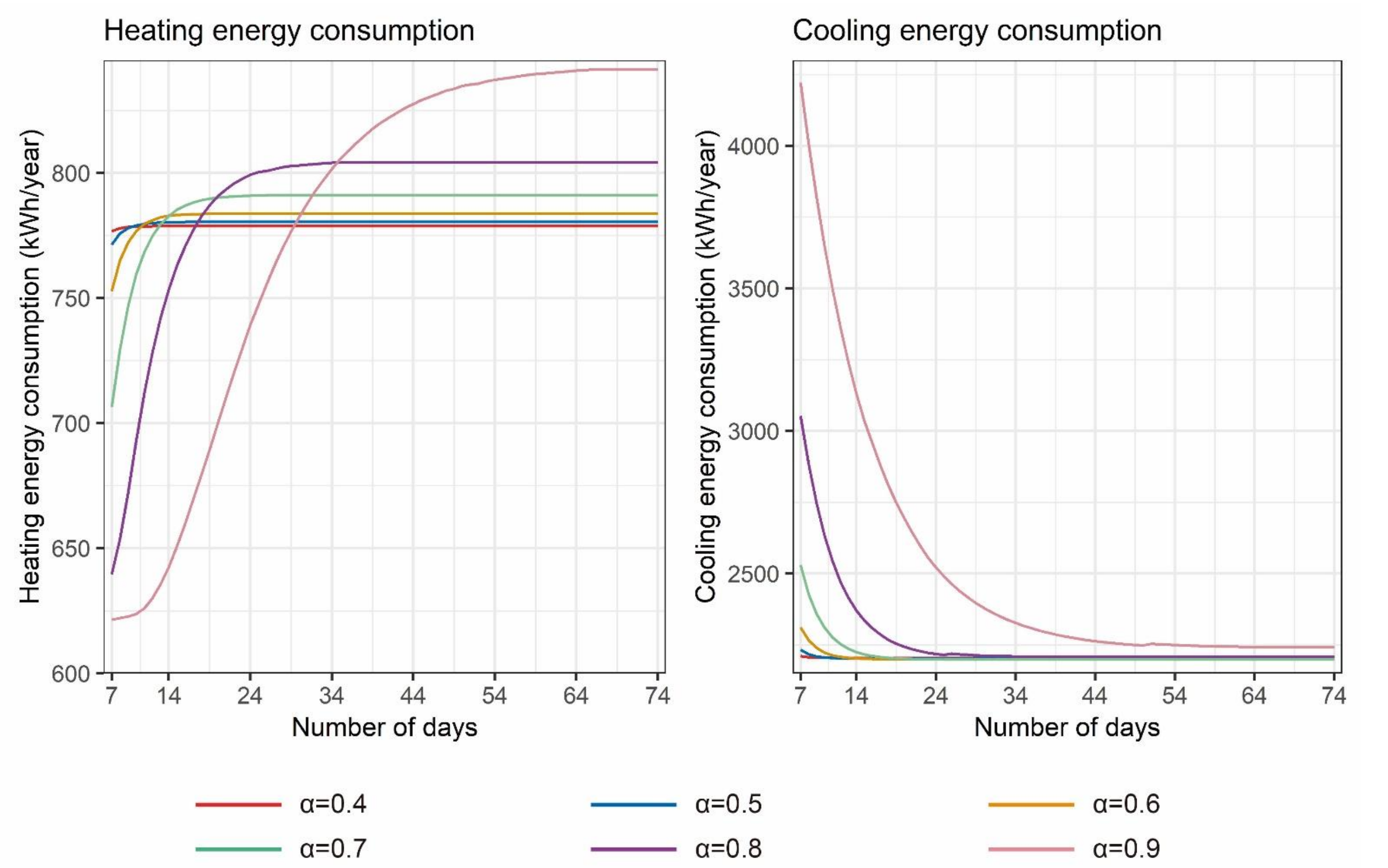

Figure 7. Variation of the energy consumption of the case study in Seville according to the α-value and the number of days used in the calculation of the prevailing mean outdoor temperature.

Table 7. Percentage deviation of the energy consumption in the thermal models calculated between 7 and the day in which each α-value is stabilized.

City	α-value	Number of days	Percentage deviation of the energy consumption [%]	
			Heating energy consumption	Cooling energy consumption
Avila	0.4	8	0.01	-0.63
	0.5	11	0.06	-2.83
	0.6	15	0.20	-9.30
	0.7	22	0.55	-23.41
	0.8	35	1.00	-44.44
	0.9	74	0.83	-60.85
Madrid	0.4	8	0.04	-0.35
	0.5	11	0.18	-1.83
	0.6	15	0.70	-6.02
	0.7	22	1.91	-15.78
	0.8	35	3.71	-32.29
	0.9	74	3.86	-48.34
Seville	0.4	8	0.25	-0.31
	0.5	11	1.18	-1.40
	0.6	15	4.11	-4.84
	0.7	22	11.99	-13.12
	0.8	35	25.54	-27.54
	0.9	74	25.91	-43.64

3.2. Energy saving analysis

Despite the variations presented by the energy consumption due to $\overline{t_{pma(out)}}$, the energy saving obtained by the adaptive setpoint temperatures was similar to that obtained by the static setpoint temperatures set in the Spanish Building Technical Code. The results were analysed by using adaptive setpoint temperatures calculated by different α-values using the number of days in which the stabilization was achieved (see Table 7). Fig. 8 shows the hourly energy consumption values obtained in the simulations. The use of the adaptive setpoint temperatures decreased the hourly energy consumption with respect to the static setpoint temperatures. In this sense, the hourly adaptive energy consumption values had a greater approximation to the axis of abscissas than the static values, with a decrease in the maximum values recorded. This tendency was found in the 3 climate zones: (i) in Avila, the maximum values of heating and cooling with static setpoint temperatures were 8.00 and 5.74 kWh, respectively, whereas the maximum values of adaptive setpoint temperatures ranged between 3.64 and 3.65 kWh in heating and between 2.63 and 2.86 kWh in cooling. Also, the average value of heating and cooling consumption of the static setpoint temperatures was 0.78 and 0.11 kWh, respectively, whereas the average values of heating and cooling adaptive setpoint temperatures ranged between 0.62 and 0.63 and between 0.035 and 0.05 kWh, respectively; (ii) in Madrid, the maximum values of heating and cooling with static setpoint temperatures were 6.77 and 9.37 kWh, respectively, whereas the maximum values of the adaptive setpoint temperatures ranged between 2.80 and 2.81 kWh in heating and between 4.03 and 4.64 kWh in cooling. The average value of heating and cooling consumption of the static setpoint temperatures was 0.46 and 0.32 kWh, respectively, whereas the average values of heating and cooling adaptive setpoint temperatures ranged between 0.34 and 0.35 and between 0.15 and 0.17 kWh, respectively; (ii) in Seville, the maximum values of heating and cooling with static setpoint temperatures were 5.21 and 13.26 kWh, respectively, whereas the maximum values of the adaptive setpoint temperatures ranged between 1.63 and 1.76 kWh in heating and between 4.96 and 4.97 kWh in cooling. The average value of heating and cooling consumption with static setpoint temperatures was 0.14 and 0.48 kWh, respectively, whereas the average values of heating and cooling adaptive setpoint temperatures ranged between 0.08 and 0.09 and between 0.25 and 0.27 kWh, respectively. The use of the adaptive setpoint temperatures greatly decreased the hourly energy consumption values, reducing the hourly consumption up to 8.3 kWh in the most unfavourable days when HVAC systems operated.

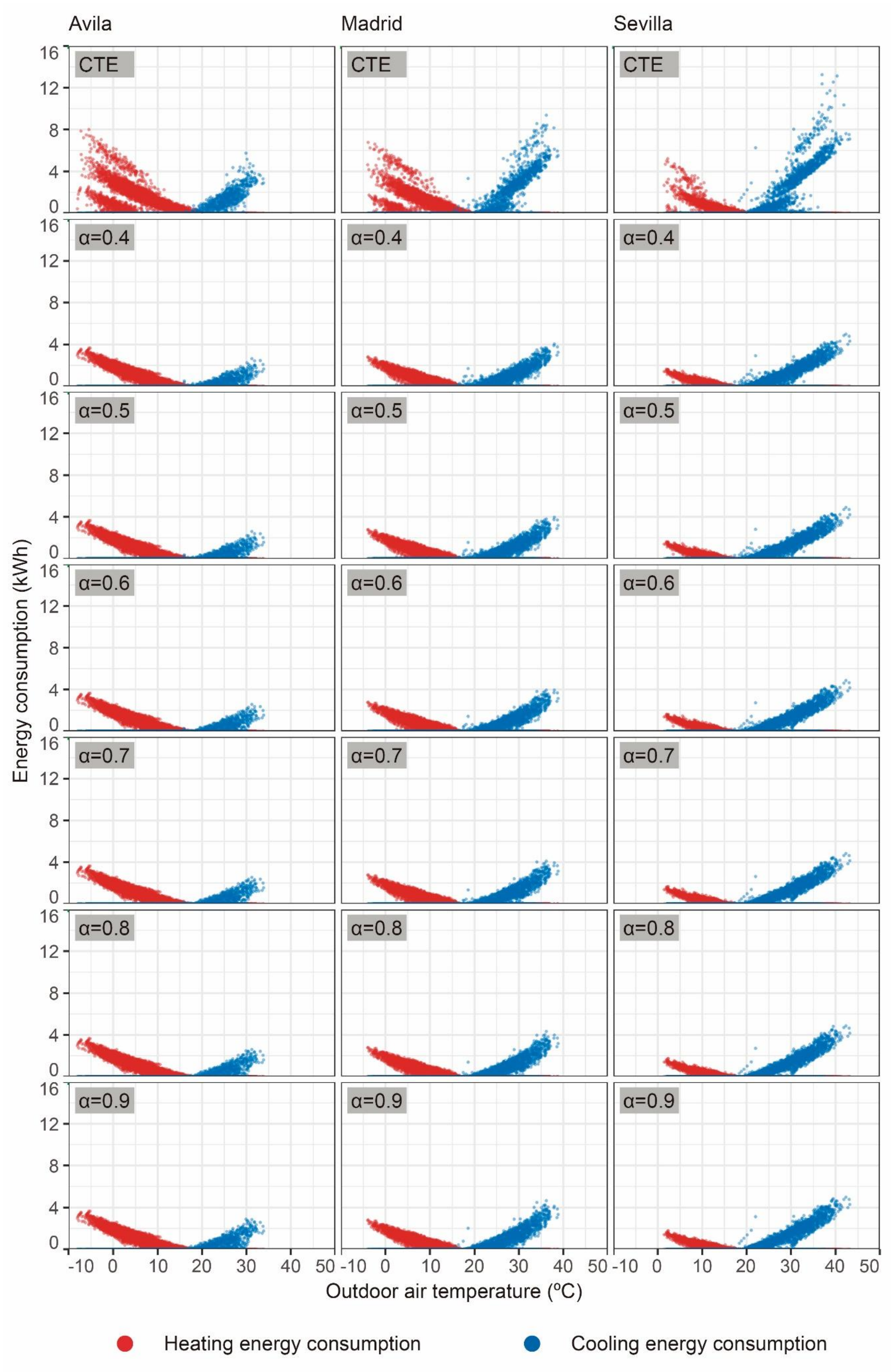

Figure 8. Variation of the hourly energy consumption between the static and adaptive setpoint temperatures in the 3 cities.

The tendency was found in annual energy consumptions. Figure 9 represents the total energy consumptions obtained through the hourly energy consumption values included in Figure 8. Although point clouds of Figure 8 had similar distributions for the different α-values, little differences were found in the annual consumption. So, an α-value of 0.5 achieved greater energy savings in the three climate zones: (i) in Avila, a saving of 25.73% in the total energy consumption; (ii) in Madrid, a saving of 35.62% in the total energy consumption; and (iii) in Seville, a saving of 44.89% in the total energy consumption. The modification of the use of the HVAC system of the case study in the 3 cities therefore achieved important savings. This fundamental aspect stresses the importance of using adaptive setpoint temperatures as important savings are obtained in the energy consumption of a building without making a huge economic investment as in other ECMs.

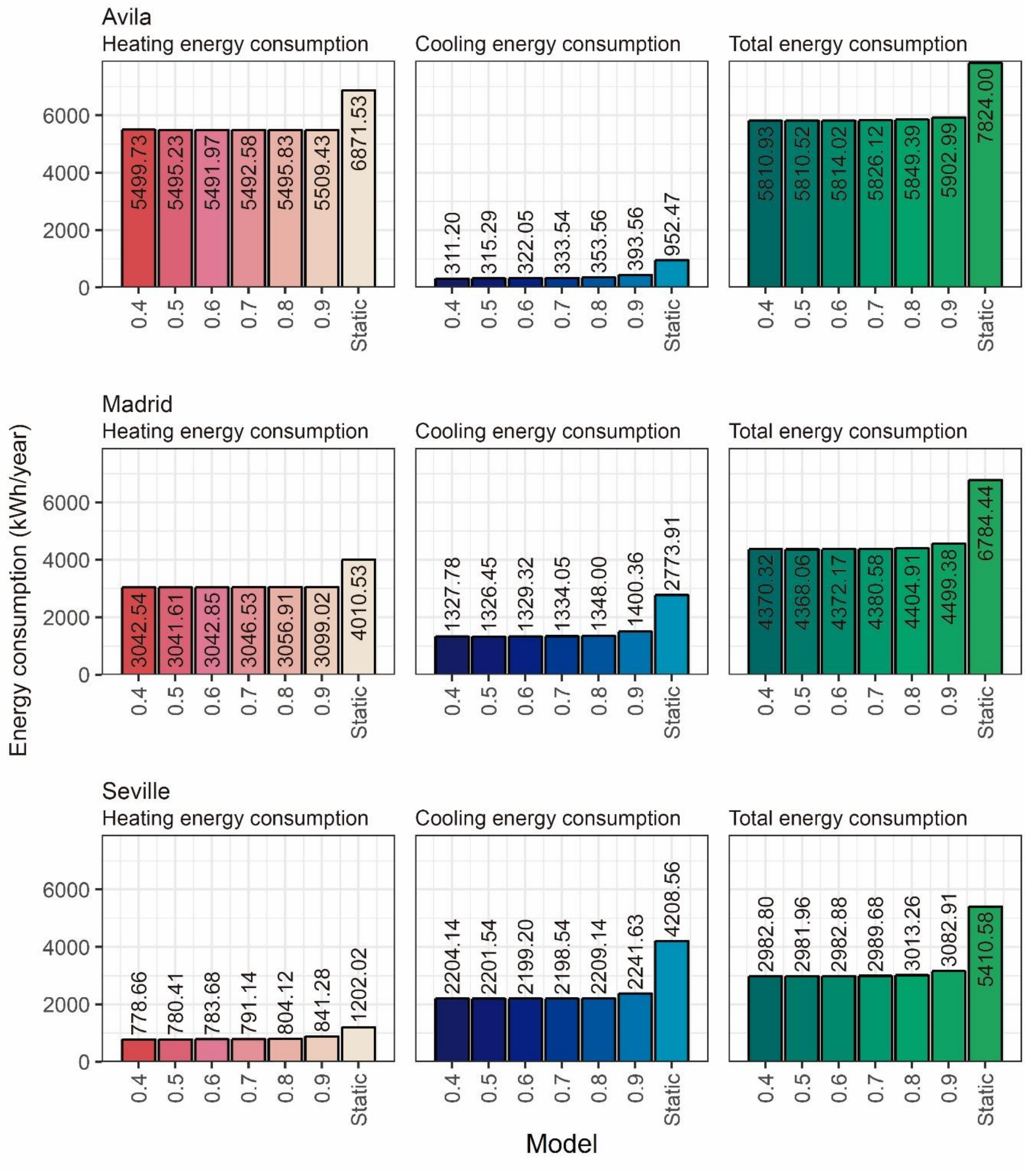

Figure 9. Variations of the annual energy consumption between the static and adaptive setpoint temperatures in the 3 cities.

It is also imperative to stress that the energy saving values correspond to the use of a homogeneous adaptive thermal model in which the adaptive setpoint temperatures were calculated by using the same $\overline{t_{pma(out)}}$ (i.e., they are based on the same α-value and the same sum of previous days). Figure 9, however, shows that a variation of an α-value of 0.5 greatly decreased the heating and cooling energy consumption in Avila and Seville: (i) in Avila, the use of an α-value of 0.6 obtained the lowest heating consumption, whereas the lowest cooling consumption was obtained with an α-value of 0.4; and (ii) in Seville, the use of an α-value of 0.4 and 0.7 achieved greater decreases in heating and cooling consumption, respectively. For this reason, the energy saving obtained by the adaptive models with both an α-value of 0.5 and the optimal combination of α-values were analysed. Moreover, the number of 7 days in the calculation of the heating setpoint temperatures was used in this analysis for the optimal combinations of α-values because the setpoint temperatures obtained a lower energy consumption (see Figures 5-7). Table 8 includes the results of energy consumption and the configurations of the optimal adaptive models. The use of optimal adaptive models implied a slight decrease of the energy consumption with respect to the adaptive model of 0.5. The deviation of the heating energy consumption ranged between 0.19 and 0.47%, of the cooling energy consumption between 0 and 1.30%, and of the total energy consumption between 0.13 and 0.33%. Although reduction percentage values of the optimal adaptive model were low, the possibility of using a more optimal adaptive model appropriate to the characteristics of the climate zone would ensure a greater energy performance of the building, due to the effect of the household-scale on the country-scale [22]. The effect of the little energy saving achieved by the optimal adaptive model can have great repercussions if the possibilities of using the thermal model is considered in many buildings. Anyway, the possibility of using an adaptive model with the same configuration for lower and upper limits would guarantee an acceptable energy performance of the building. The results of this study therefore suggest two possibilities of using adaptive setpoint temperatures: firstly, determining an acceptable value of α-value and the number of days for upper and lower limits in the climate zone in which the building is, and secondly, determining the optimal configuration for both limits. It is worth stressing that the α-value should be acceptably determined from the perspective of both energy saving and thermal comfort due to its impact on the internal conditions required and the climate variability [66].

Table 8. Comparison between the energy consumption obtained by the adaptive model using an α-value of 0.5 and the optimal adaptive model.

City	Adaptive model of 0.5				Optimal Adaptive model			
	Configuration	Energy consumption [kWh/year]			Configuration	Energy consumption [kWh/year]		
		Heating	Cooling	Total		Heating	Cooling	Total
Avila	Heating: α-value =0.5 Number of days: 11 Cooling: α-value =0.5 Number of days: 11	5,495.23	315.29	5,810.52	Heating: α-value =0.6 Number of days: 7 Cooling: α-value =0.4 Number of days: 8	5,479.94	311.20	5,791.14
Madrid	Heating: α-value =0.5 Number of days: 11 Cooling: α-value =0.5 Number of days: 11	3,041.61	1,326.45	4,368.06	Heating: α-value =0.5 Number of days: 7 Cooling: α-value =0.5 Number of days: 11	3,035.75	1,326.45	4,362.20
Seville	Heating: α-value =0.5 Number of days: 11 Cooling: α-value =0.5 Number of days: 11	780.41	2,201.54	2,981.96	Heating: α-value =0.4 Number of days: 7 Cooling: α-value =0.7 Number of days: 22	776.73	2,198.54	2,975.27

The importance of the results is worth stressing with respect to previous research works. First, the use of an α-value of 0.5 is a greater approximation to the value recommended by ASHRAE 55-2017 [35], which indicates that an α-value of 0.6 should be used in middle latitudes (i.e., latitudes between -23.4394444 and -66.5608333, and between 23.4394444 and 66.5608333). As the cities analysed are in latitudes between 37.383333 and 40.654347, there were limitations in the α-value recommended by ASHRAE 55-2017. A detailed analysis of the characteristics of each climate zone would determine the α-value obtaining a greater saving in the total consumption by using adaptive setpoint temperatures, keeping an acceptability of 80%.

Second, most studies on adaptive setpoint temperatures consider the use of an α-value of 0.8 and the number of 7 days in the calculation of the $\overline{t_{pma(out)}}$ according to the recommendation of EN 15251: 2007 [27,28,39]. Most studies were focused on Seville [27,28], although others analysed the other two cities considered [34,39]. The use of the configuration of $\overline{t_{pma(out)}}$ obtained important energy savings in the case studies analysed in each research. However, the results of this study show that determining the α-value and the number of days correctly allows the energy saving to be optimized, so the energy saving results obtained in previous studies may be better if the calculation of the adaptive setpoint temperatures is previously analysed.

4. Conclusions

This paper analyses the influence of the prevailing mean outdoor air temperature on the energy saving obtained with adaptive setpoint temperatures, mainly due to the influence of two factors on the prevailing mean outdoor temperature:

the α-value and the number of previous days considered. For this purpose, a representative case study located in 3 cities previously analysed in other research studies (Avila, Madrid, and Seville) was used. The adaptive thermal comfort model used in this study was the category of acceptability of 80% of ASHRAE 55-2017.

As a result, the influence of the prevailing mean outdoor temperature on the energy saving potential has been studied. The accurate analysis of the two factors required for its calculation allows greater reductions in the energy saving of the building to be obtained. The α-values between 0.4 and 0.6 were found to have the lowest energy consumption. The use of a low number of previous days also achieved greater reductions in heating energy consumption, whereas the maximum number of days of each α-value was applied to cooling energy consumption.

There were differences in the optimal α-value obtained in the 3 cities with those used in other research studies, where a value of 0.8 was used as EN 15251:2007 recommends. However, the use of a value of 0.5 obtained a greater energy saving than using the value recommended by EN 15251. Likewise, the optimal α-value is different to that recommended by ASHRAE 55-2017 because of the latitude of the cities analysed (the α-value recommended by ASHRAE 55-2017 is 0.6). The need to establish a more accurate criterion in the establishment of the α-value is shown in this study. In addition, the importance of the α-value does not only depend on the energy saving achieved because of the relationship established by the α-value between the users' thermal comfort and external climate variations.

The use of individual configurations for heating and cooling adaptive setpoint temperatures achieved a lower energy consumption. For this reason, the use of optimal programming for the two typologies of setpoint was analysed in each zone. The use of optimal configurations for each type of setpoint lowly increased the energy saving. Nevertheless, if the application rate of this energy conservation measure is high, the effect of the energy reduction with the optimization of the calculation of the prevailing mean outdoor temperature can be even more important. To ensure that occupants achieve the thermal comfort, it would be required to validate through working fields which α-value is the most appropriate for each climate based on both the occupants' thermal response and the energy saving.

To conclude, the results of this research give greater information of the possibilities of using adaptive setpoint temperatures optimally to reduce the high building energy consumption. The results can also be useful for architects, engineers, energy auditors, and researchers. The use of these techniques would ensure a high energy renovation rate of the existing buildings in a short period of time and without making huge economic investments. Because of the influence of the α-value on the relationship between occupants' comfort and the external temperature, further steps of the research will be focused on the establishment of criteria to use appropriately the α-value in various latitudes and climate zones. Furthermore, the possibilities of using automatic learning techniques similar to that carried out in [41] should be evaluated in further studies to regulate setpoint temperatures depending on the external climate conditions.

References

[1] World Wildlife Fund, Living Planet Report 2014: Species and spaces, people and places, WWF International, Gland, Switzerland, 2014. doi:10.1007/s13398-014-0173-7.2.

[2] The United Nations Environment Programme, Building Design and Construction: Forging Resource Efficiency and Sustainable, Nairobi, Kenya, 2012.

[3] L. Pérez-Lombard, J. Ortiz, C. Pout, A review on buildings energy consumption information, Energy Build. 40 (2008) 394–398. doi:10.1016/j.enbuild.2007.03.007.

[4] R. Lowe, Technical options and strategies for decarbonizing UK housing, Build. Res. Inf. 35 (2007) 412–425. doi:10.1080/09613210701238268.

[5] K. Park, M. Kim, Energy Demand Reduction in the Residential Building Sector: A Case Study of Korea, Energies. 10 (2017) 1–11. doi:10.3390/en10101506.

[6] L. Di Pilla, G. Desogus, S. Mura, R. Ricciu, M. Di Francesco, Optimizing the distribution of Italian building energy retrofit incentives with Linear Programming, Energy Build. 112 (2016) 21–27. doi:10.1016/j.enbuild.2015.11.050.

[7] I. Theodoridou, A.M. Papadopoulos, M. Hegger, A typological classification of the Greek residential building stock, Energy Build. 43 (2011) 2779–2787. doi:10.1016/j.enbuild.2011.06.036.

[8] European Commission, A Roadmap for moving to a competitive low carbon economy in 2050, Brussels, Belgium, 2011.

[9] H. Thomson, S. Bouzarovski, C. Snell, Rethinking the measurement of energy poverty in Europe: A critical analysis of indicators and data, Indoor Built Environ. 26 (2017) 879–901. doi:10.1177/1420326X17699260.

[10] D. Bienvenido-Huertas, A. Pérez-Fargallo, R. Alvarado-Amador, C. Rubio-Bellido, Influence of climate on the creation of multilayer perceptrons to analyse the risk of fuel poverty, Energy Build. 198 (2019) 38–60. doi:10.1016/j.enbuild.2019.05.063.

[11] C. Liddell, C. Morris, H. Thomson, C. Guiney, Excess winter deaths in 30 European countries 1980–2013: a critical

review of methods, J. Public Health (Bangkok). 38 (2016) 806–814.

[12] J. Teller-Elsberg, B. Sovacool, T. Smith, E. Laine, Fuel poverty, excess winter deaths, and energy costs in Vermont: Burdensome for whom?, Energy Policy. 90 (2016). doi:10.1016/j.enpol.2015.12.009.

[13] R. Castaño-Rosa, J. Solís-Guzmán, C. Rubio-Bellido, M. Marrero, Towards a multiple-indicator approach to energy poverty in the European Union: A review, Energy Build. 193 (2019) 36–48. doi:10.1016/j.enbuild.2019.03.039.

[14] S. Bouzarovski, S. Petrova, A global perspective on domestic energy deprivation: Overcoming the energy poverty–fuel poverty binary, Energy Res. Soc. Sci. 10 (2015) 31–40.

[15] C. Hu, G. Jain, P. Zhang, C. Schmidt, P. Gomadam, T. Gorka, Data-driven method based on particle swarm optimization and k-nearest neighbor regression for estimating capacity of lithium-ion battery, Appl. Energy. 129 (2014) 49–55. doi:10.1016/j.apenergy.2014.04.077.

[16] B. Boardman, Fuel Poverty: From Cold Homes to Affordable Warmth, John Wiley & Sons Ltd, London, UK, 1991.

[17] K. Fabbri, Building and fuel poverty, an index to measure fuel poverty: An Italian case study, Energy. 89 (2015) 244–258. doi:10.1016/j.energy.2015.07.073.

[18] P. Nussbaumer, M. Bazilian, V. Modi, Measuring energy poverty: Focusing on what matters, Renew. Sustain. Energy Rev. 16 (2012) 231–243. doi:10.1016/j.rser.2011.07.150.

[19] N. Bonatz, R. Guo, W. Wu, L. Liu, A comparative study of the interlinkages between low carbon development and energy poverty in China and Germany by developing an energy poverty index, Energy Build. 183 (2019) 817–831. doi:https://doi.org/10.1016/j.enbuild.2018.09.042.

[20] K. Wang, Y.-X. Wang, K. Li, Y.-M. Wei, Energy poverty in China: An index based comprehensive evaluation, Renew. Sustain. Energy Rev. 47 (2015) 308–323. doi:10.1016/j.rser.2015.03.041.

[21] S. Desiere, W. Vellema, M. D'Haese, A validity assessment of the Progress out of Poverty Index (PPI)™, Eval. Program Plann. 49 (2015) 10–18. doi:10.1016/j.evalprogplan.2014.11.002.

[22] G. Besagni, M. Borgarello, The determinants of residential energy expenditure in Italy, Energy. 165 (2018) 369–386.

[23] D. Brounen, N. Kok, J.M. Quigley, Residential energy use and conservation: Economics and demographics, Eur. Econ. Rev. 56 (2012) 931–945. doi:10.1016/j.euroecorev.2012.02.007.

[24] M. Filippini, S. Pachauri, Elasticities of electricity demand in urban Indian households, Energy Policy. 32 (2004) 429–436. doi:10.1016/S0301-4215(02)00314-2.

[25] N.A. Kurekci, Determination of optimum insulation thickness for building walls by using heating and cooling degree-day values of all Turkey's provincial centers, Energy Build. 118 (2016) 197–213. doi:10.1016/j.enbuild.2016.03.004.

[26] E.L. Vine, E. Kazakevicius, Residential energy use in Lithuania: The prospects for energy efficiency, Energy. 24 (1999) 591–603. doi:10.1016/S0360-5442(99)00013-4.

[27] D. Sánchez-García, C. Rubio-Bellido, M. Marrero Meléndez, F.J. Guevara-García, J. Canivell, El control adaptativo en instalaciones existentes y su potencial en el contexto del cambio climático, Hábitat Sustentable. 7 (2017) 06–17. http://revistas.ubiobio.cl/index.php/RHS/article/view/2924.

[28] D. Sánchez-García, C. Rubio-Bellido, J.J.M. del Río, A. Pérez-Fargallo, Towards the quantification of energy demand and consumption through the adaptive comfort approach in mixed mode office buildings considering climate change, Energy Build. 187 (2019) 173–185. doi:10.1016/j.enbuild.2019.02.002.

[29] Z. Ren, D. Chen, Modelling study of the impact of thermal comfort criteria on housing energy use in Australia, Appl. Energy. 210 (2018) 152–166. doi:10.1016/j.apenergy.2017.10.110.

[30] W. Tushar, T. Wang, L. Lan, Y. Xu, C. Withanage, C. Yuen, K.L. Wood, Policy design for controlling set-point temperature of ACs in shared spaces of buildings, Energy Build. 134 (2017) 105–114. doi:10.1016/j.enbuild.2016.10.027.

[31] M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden, C.E. Hanson, Contribution of working group II to the fourth assessment report of the intergovernmental panel on climate change, Cambridge University Press, 2007.

[32] K.K.W. Wan, D.H.W. Li, J.C. Lam, Assessment of climate change impact on building energy use and mitigation measures in subtropical climates, Energy. 36 (2011) 1404–1414. doi:10.1016/j.energy.2011.01.033.

[33] G.N. Spyropoulos, C.A. Balaras, Energy consumption and the potential of energy savings in Hellenic office buildings used as bank branches - A case study, Energy Build. 43 (2011) 770–778. doi:10.1016/j.enbuild.2010.12.015.

[34] C. Sánchez-Guevara Sánchez, A. Mavrogianni, F.J. Neila González, On the minimal thermal habitability conditions in low income dwellings in Spain for a new definition of fuel poverty, Build. Environ. 114 (2017) 344–356.

doi:10.1016/j.buildenv.2016.12.029.

[35] American Society of Heating Refrigerating and Air Conditioning Engineers (ASHRAE), ASHRAE Standard 55-2017 Thermal Environmental Conditions for Human Occupancy, Atlanta, GA, United States, 2017.

[36] A.C. van der Linden, A.C. Boerstra, A.K. Raue, S.R. Kurvers, R.J. De Dear, Adaptive temperature limits: A new guideline in the Netherlands: A new approach for the assessment of building performance with respect to thermal indoor climate, Energy Build. 38 (2006) 8–17. doi:10.1016/j.enbuild.2005.02.008.

[37] A.C. Boerstra, J. van Hoof, A.M. van Weele, A new hybrid thermal comfort guideline for the Netherlands: background and development, Archit. Sci. Rev. 58 (2015) 24–34. doi:10.1080/00038628.2014.971702.

[38] R. Kramer, J. van Schijndel, H. Schellen, Dynamic setpoint control for museum indoor climate conditioning integrating collection and comfort requirements: Development and energy impact for Europe, Build. Environ. (2017). doi:10.1016/j.buildenv.2017.03.028.

[39] D. Sánchez-García, D. Bienvenido-Huertas, M. Tristancho-Carvajal, C. Rubio-Bellido, Adaptive Comfort Control Implemented Model (ACCIM) for Energy Consumption Predictions in Dwellings under Current and Future Climate Conditions: A Case Study Located in Spain, Energies. 12 (2019) 1498. doi:10.3390/en12081498.

[40] P. Aparicio-Ruiz, E. Barbadilla-Martín, J.M. Salmerón-Lissén, J. Guadix-Martín, Building automation system with adaptive comfort in mixed mode buildings, Sustain. Cities Soc. 43 (2018) 77–85. doi:10.1016/j.scs.2018.07.028.

[41] D. Bienvenido-Huertas, C. Rubio-Bellido, J. Pérez-Ordóñez, F. Martínez-Abella, Estimating Adaptive Setpoint Temperatures Using Weather Stations, Energies. 12 (2019) 1197. doi:10.3390/en12071197.

[42] A. Pérez-Fargallo, J.A. Pulido-Arcas, C. Rubio-Bellido, M. Trebilcock, B. Piderit, S. Attia, Development of a new adaptive comfort model for low income housing in the central-south of chile, Energy Build. 178 (2018) 94–106. doi:10.1016/j.enbuild.2018.08.030.

[43] S. Sorrell, Reducing energy demand: A review of issues, challenges and approaches, Renew. Sustain. Energy Rev. 47 (2015) 74–82. doi:10.1016/j.rser.2015.03.002.

[44] S. Sorrell, Improving the evidence base for energy policy: The role of systematic reviews, Energy Policy. 35 (2007) 1858–1871. doi:10.1016/j.enpol.2006.06.008.

[45] H.D. Saunders, Recent evidence for large rebound: Elucidating the drivers and their implications for climate change models, Energy J. 36 (2015) 23–48. doi:10.5547/01956574.36.1.2.

[46] S. Seebauer, The psychology of rebound effects: Explaining energy efficiency rebound behaviours with electric vehicles and building insulation in Austria, Energy Res. Soc. Sci. 46 (2018) 311–320. doi:10.1016/j.erss.2018.08.006.

[47] A. Wolff, J. Schubert, B. Gill, Risiko energetische Sanierung?, in: K. Großmann, A. Schaffrin, C. Smigiel (Eds.), Energ. Und Soz. Ungleichheit Zur Ges. Dimens. Der Energiewende Deutschl. Und Eur., Springer Fachmedien Wiesbaden, Wiesbaden, 2017: pp. 611–634. doi:10.1007/978-3-658-11723-8_23.

[48] R. Galvin, M. Sunikka-Blank, Economic viability in thermal retrofit policies: Learning from ten years of experience in Germany, Energy Policy. 54 (2013) 343–351. doi:10.1016/j.enpol.2012.11.044.

[49] European Committee for Standardization, EN 15251:2007 Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor quality, thermal environment, lighting and acoustics, European Committee for Standardization, Brussels, 2007.

[50] European Committee for Standardization, EN 16798-1:2019 Energy performance of buildings - Ventilation for buildings - Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acous, 2019.

[51] S. Carlucci, L. Bai, R. de Dear, L. Yang, Review of adaptive thermal comfort models in built environmental regulatory documents, Build. Environ. 137 (2018) 73–89. doi:10.1016/j.buildenv.2018.03.053.

[52] A. Roetzel, A. Tsangrassoulis, U. Dietrich, Impact of building design and occupancy on office comfort and energy performance in different climates, Build. Environ. 71 (2014) 165–175. doi:10.1016/j.buildenv.2013.10.001.

[53] J.M. Blanco, A. Buruaga, J. Cuadrado, A. Zapico, Assessment of the influence of façade location and orientation in indoor environment of double-skin building envelopes with perforated metal sheets, Build. Environ. 163 (2019) 106325. doi:10.1016/j.buildenv.2019.106325.

[54] The Government of Spain, Royal Decree 2429/79. Approving the Basic Building Norm NBE-CT-79, about the Thermal Conditions in Buildings, 1979.

[55] F. Kurtz, M. Monzón, B. López-Mesa, Energy and acoustics related obsolescence of social housing of Spain's post-war in less favoured urban areas. The case of Zaragoza, Inf. La Construcción. 67 (2015) m021. doi:10.3989/ic.14.062.

[56] Spanish Institute of Statistics, Population and Housing Census, (2011). https://www.ine.es/censos2011_datos/cen11_datos_resultados.htm# (accessed November 9, 2018).

[57] A. Guajardo, Análisis tipológico de bloques lineales de vivienda social: España 1950-1983. El caso de Andalucía occidental, Inf. La Construcción. 69 (2017) 185. doi:10.3989/ic.16.055.

[58] D. Bienvenido-Huertas, J. Moyano, C.E. Rodríguez-Jiménez, D. Marín, Applying an artificial neural network to assess thermal transmittance in walls by means of the thermometric method, Appl. Energy. 233–234 (2019) 1–14. doi:10.1016/j.apenergy.2018.10.052.

[59] D. Bienvenido-Huertas, C. Rubio-Bellido, J.L. Pérez-Ordóñez, J. Moyano, Optimizing the evaluation of thermal transmittance with the thermometric method using multilayer perceptrons, Energy Build. 198 (2019) 395–411. doi:10.1016/j.enbuild.2019.06.040.

[60] G. Ficco, F. Iannetta, E. Ianniello, F.R. D'Ambrosio Alfano, M. Dell'Isola, U-value in situ measurement for energy diagnosis of existing buildings, Energy Build. 104 (2015) 108–121. doi:10.1016/j.enbuild.2015.06.071.

[61] American National Standards Institute/American Society of Heating Refrigerating and Air-Conditioning Engineers (ANSI/ASHRAE), ASHRAE Guideline 14-2014: Measurement of Energy, Demand, and Water Savings, 2014.

[62] D. Coakley, P. Raftery, M. Keane, A review of methods to match building energy simulation models to measured data, Renew. Sustain. Energy Rev. 37 (2014) 123–141. doi:10.1016/j.rser.2014.05.007.

[63] The Government of Spain, Royal Decree 314/2006. Approving the Spanish Technical Building Code, Madrid, Spain, 2013.

[64] F. Rubel, M. Kottek, Observed and projected climate shifts 1901-2100 depicted by world maps of the Köppen-Geiger climate classification, Meteorol. Zeitschrift. 19 (2010) 135–141. doi:10.1127/0941-2948/2010/0430.

[65] METEONORM, Handbook part II: Theory (Version 7.3.1), Bern, Switzerland, 2019.

[66] F. Nicol, M. Humphreys, Derivation of the adaptive equations for thermal comfort in free-running buildings in European standard EN15251, Build. Environ. 45 (2010) 11–17. doi:10.1016/j.buildenv.2008.12.013.