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Analysis of the Impact of the Use Profile of HVAC Systems Established by the Spanish Standard to Assess Residential Building Energy Performance

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Abstract: State regulations play an important role to guarantee an appropriate building energy performance. As for the Spanish regulation, the limitation of energy consumption should be analyzed with simulation tools by using operational profiles. The profile of operational conditions of HVAC systems in residential buildings limits the use of heating and cooling systems. This paper studied the limitations of the residential profile in energy assessment processes through simulation tools. A case study was analyzed with three operational approaches and was placed in 8131 Spanish cities. The results showed that the use limitations of cooling systems lead to ignorance of an important percentage contribution in the cooling energy demand in some months of the year. The use of an operational profile with an extended calendar for cooling systems for the entire year would imply a more appropriate knowledge of the building energy performance in order to know the fulfilment of the state regulation and its correct energy classification.

Keywords: residential profile; building energy performance; Spanish standard; use of HVAC systems; cooling energy demand

1. Introduction

Global warming is leading to a new habitat scenario in which the cases of environmental degradation, rise of the sea level, and extinction of ecosystems are increasing [1]. National and interregional governments are developing legislation to reduce greenhouse gas (GHG) emissions. The high energy consumption of the building sector is among the main contributors [2,3]. The deficient energy performance of most building stock causes high energy consumption [4,5]. This aspect takes place mainly in the countries in the south of Europe, where most buildings were designed and built in periods before the first regulations on energy efficiency [6,7]. In addition, other increasing problems in recent years, such as energy poverty [8] and the increase of the death rate due to inappropriate indoor thermal conditions [9,10], increase the need for improving the building stock performance. The European Union has established the requirement that all member countries should reduce the GHG emissions from the building stock by 90% in 2050. For this, it is necessary to reduce the building energy consumption while keeping adequate indoor thermal conditions [11].

To ensure an appropriate energy performance of new or restored buildings, predicting the energy performance of buildings is required. For this purpose, energy simulation tools are used to estimate the building energy consumption [12] and, according to the regulations of each country, various energy label methods are available [13]. These tools constitute a fundamental data source to know the state of the building stock in a region [14] or in a country [15]. In addition, they can be used to know the environmental impact of the building stock [16]. Energy consumption simulations are directly related to six factors [17]: three technical and physical factors (climate, building envelope, and building equipment) and three social factors (operation and maintenance, occupant behavior, and indoor environment conditions). So the energy performance of a building depends not just on technical characteristics (e.g., the thermal performance of the façade) but also on users' behavior.

Regardless of the influence of occupancy patterns on energy consumption [18–20], several research studies have proven that the use of heating ventilation and air conditioning (HVAC) systems affects building energy performance. This use can be specified either by operation schedules or by indoor setpoint temperatures. As for indoor setpoint temperatures, various studies have stressed the variations in the energy consumption by using different values: (i) Parry et al. [21] analyzed the possibilities of reducing the energy consumption of an office building in Zurich and an increase of between 2 and 4 °C of the cooling setpoint temperature reduced the annual energy consumption by one third. (ii) A similar study was conducted by Wan et al. [22], who analyzed an office building in Hong Kong; the use of cooling setpoint temperatures greater than 25.5 °C achieved high energy savings in all scenarios (both current and future). (iii) Spyropoulos and Balaras [23] analyzed several bank branches located in Greece; the use of setpoint temperatures of 20 °C for heating and 26 °C for cooling reduced the total energy consumption by 45%. (iv) Sánchez-García et al. [24] studied the possibility of using setpoint temperatures adapted to adaptive thermal comfort models in an office building in Spain; the results showed reductions of the energy demand by 31.34% for the category I from EN 15251:2007 and by 69.91% for the category III. Likewise, the use of HVAC systems could vary the feasibility of energy conservation measures, so using HVAC systems appropriately could imply a saving similar to the improvement of the envelope without economic investments [25], thus constituting an opportunity for low-income households and those at risk of energy poverty [26].

Therefore, the use of HVAC systems influences the building energy consumption [27]. To ensure that the analyzed building has an appropriate energy performance, regulatory tools should be available to establish criteria on energy performance to be fulfilled. Regarding the Spanish regulation, all buildings should guarantee the fulfilment of the requirements established by the Spanish Building Technical Code (CTE in Spanish) [28]. The energy regulation from the CTE has been developed since 2006, with three important modifications in 2009, 2013, and 2020 (this last modification is focused on the definition of nearly zero energy consumption buildings [29]). The CTE establishes the calculation procedure required to determine the building energy consumption. Among other aspects, some usage profiles that vary according to the type of building (residential or non-residential) are defined, and a comfort model based on the Predicted Mean Vote is used [30]. These profiles are also used by the Spanish energy certification tools, such as the unified Lider-Calener (HULC) tool. Regarding the residential profile, operational conditions have various characteristics according to the type of system used (see Table 1): (i) for heating systems, a continuous use throughout the day is considered (varying the indoor setpoint temperature at 17 or 20 °C, according to the hour of the day) with a use established for the months from October to May; and (ii) for cooling systems, a use during the months between June and September is considered, with indoor setpoint temperatures of 25 and 27 °C, according to the hour of the day. Unlike heating systems, the period from 07:00 to 14:59 is considered when a setpoint temperature is not established (i.e., the cooling system is not used). This aspect raises the question of whether the residential profile used in the CTE fulfils the limitations of the cooling energy consumption of the building designed. In this regard, the conditions for using the cooling system do not correspond to the occupancy conditions established in the CTE residential profile, as the same occupancy percentage is considered in the time period from 07:00 to 14:59 in both heating and cooling periods, so the heating system meets the heating demand in that time zone, unlike the cooling system. There is therefore an occupancy in the central hours of the day in the summer season in which the regulation considers that the use of the building does not guarantee the users' thermal comfort. Although it is true that users under actual conditions can achieve the thermal comfort regardless of the regulatory conditions defined by the CTE, such as in the case of the adaptive thermal comfort strategies [31,32], the regulatory operational conditions established by the CTE should guarantee that the results are representative of the actual energy demands of buildings. In such a way, the results of energy demand and energy consumption would not be conditioned before analyzing the energy performance, and the percentage contributions of the heating and the cooling energy consumption of a building could vary throughout the year.

Table 1. Operational conditions of the indoor spaces in residential buildings according to the Spanish Building Technical Code (CTE).

Type	Period	Time/Indoor Setpoint Temperature (°C)			
		0:00–6:59	07:00–14:59	15:00–22:59	23:00–23:59
Heating setpoint temperature	From January to May	17	20	20	17
	From June to September	-	-	-	-
	From October to December	17	20	20	17
Cooling setpoint temperature	From January to May	-	-	-	-
	From June to September	27	-	25	27
	From October to December	-	-	-	-

Some studies have addressed the advantages and limitations of the CTE specifications based on the energy simulation analysis. López-Ochoa et al. [33,34] analyzed the trends in the implementation of the nearly zero energy building (nZEB) in Spain with the CTE. The results showed the possibility of implementing nZEB through future modifications of this code. Then, López-Ochoa et al. [29] complemented the analysis of the previous works by considering the production of renewable energy in buildings in accordance with the new CTE requirements. Likewise, several studies have based their results on energy simulations with the CTE residential profile or have used Spanish energy certification tools: (i) Suárez and Fragoso [35] analyzed social housing located in hot areas from Spain; (ii) Rodríguez-Jiménez et al. [36] evaluated the importance of the envelope airtightness in the energy demand of buildings in southern Spain; (iii) Irulegi et al. [37] analyzed the efficacy of ventilated façades in 192 case studies; (iv) Montalbán Pozas [38] studied the energy poverty risk in 25 dwellings; and (v) Sánchez-García et al. [39] analyzed the application of adaptive setpoint temperatures.

However, these studies have not considered the influence of the operational pattern of the CTE. One of the most outstanding aspects of the CTE residential profile is that air conditioning systems can be used only in the summer months. However, recent studies have highlighted the high incidence of cooling energy demand in non-summer months such as May or October [40]. Thus, there may be a risk of devaluing the importance of air conditioning systems with the CTE's residential profile. The use of this type of profile can make it difficult to calibrate the simulated models [41] and increase the deviations between the actual and the simulated energy performance of buildings [42]. For this reason, the analysis of the limitations of the operational pattern of the CTE is crucial. Some studies have analyzed the limitations of operational profiles while focusing on load profiles. Cuerda et al. [18,43] assessed the limitations associated with the loads of the CTE residential profile. However, there are no studies that analyze the operational limitations of HVAC systems in the CTE residential profile. For this reason, this study presents the possibilities of increasing the energy consumption of the buildings analyzed by the CTE under various operational conditions for HVAC systems. Starting from the residential profile established by the CTE, the effect of considering the use periods of heating and cooling systems throughout the year was first analyzed because of the tendencies found in the monthly energy consumptions in several case studies analyzed in Spain [44,45], where there was a heating or cooling energy demand in the months not considered by the CTE's residential profile (e.g., the cooling energy demand in May). Then, the effect of using the cooling system with an indoor setpoint temperature of 25 °C in the time period from 07:00 to 14:59 was analyzed. The whole analysis was conducted by using a case study designed according to the regulatory specifications established by the last modification of the CTE. This case study was placed in the 8131 Spanish cities. The simulations were performed with EnergyPlus. As three use approaches of the HVAC systems were analyzed (operational conditions of the CTE, operational conditions of the CTE increasing the use of heating and cooling systems throughout the year, and the use of the cooling system from 07:00 to 14:59), as well as a case study with each approach of the operational conditions in the 8131 cities, the results of this paper were based on 24,393 energy simulations.

2. Methodology

This study aims to analyze the limitations to estimating the energy performance of buildings designed according to the CTE by using the residential profile. For this purpose, three approaches of the operational conditions of the interior of a case study located in the 8131 Spanish cities are analyzed. The following subsections specify the details related to the climate classification and thermal demands included in the CTE, and the case study and the simulation procedure are described as well.

2.1. Climate Zones from the CTE and Limitations of the Thermal Properties of the Envelope

The Spanish climate classification to establish the requirements for building energy efficiency has been changed continually from the first regulation on energy efficiency in 1979 (NBE-CT-79 [46]). The current regulatory framework (the CTE) establishes a different climate classification according to the winter (*WCS*) and the summer (*SCS*) climate severity. The winter season (or heating demand season) corresponds to the months from October to May, and the summer season (or cooling demand season) corresponds to the months from June to September. Thus, the CTE does not consider intermediate seasons because winter conditions are applied to the spring and autumn months. Therefore, the associated limitations of extending winter conditions (i.e., the use of heating systems) to the intermediate months should be known, as well as the non-use of air conditioning systems. The values of *WCS* and *SCS* are obtained through the degree-days based on 20 °C obtained in both seasons (see Equations (1) and (2)). After obtaining these values, the labels for *WCS* and *SCS* can be determined (see Table 2). Winter climate zone (WCZ) is classified with a letter between α and E, and summer climate zone (SCZ) is classified with a number between 1 and 4. This classification is an indicator of the climate severity of the region, as labels close to E indicate a great severity of the city in winter, whereas values close to 4 indicate a great severity in summer. A total of 15 climate zones are obtained by combining WCZ and SCZ. Figure 1 represents the climate classification of the 8131 Spanish cities according to the data included in the CTE.

$$WCS = 3.546{\cdot}10^{-4}{\cdot}DD_W - 4.043{\cdot}10^{-1}{\cdot}\frac{n}{N} + 8.394{\cdot}10^{-8}{\cdot}DD_W^2 - 7.325{\cdot}10^{-2}{\cdot}\left(\frac{n}{N}\right)^2 - 1.137{\cdot}10^{-1}, \quad (1)$$

$$SCS = 2.990{\cdot}10^{-3}{\cdot}DD_S - 1.1597{\cdot}10^{-7}{\cdot}DD_S^2 - 1.713{\cdot}10^{-1}, \quad (2)$$

where DD_W is the mean degree-days based on 20 °C in winter (between October and May); $\frac{n}{N}$ is the quotient between the number of hours of sun (n) and the maximum hours of sun (N) between October and May; and DD_S is the mean degree-days based on 20 °C in summer (between June and September).

Table 2. Classification intervals for winter (*WCS*) and summer (*SCS*) climate severity.

Intervals for *WCS*		**Intervals for *SCS***	
Class	**Value**	**Class**	**Value**
α	$WCS \leq 0$	1	$SCS \leq 0.50$
A	$0 < WCS \leq 0.23$	2	$0.50 < SCS \leq 0.83$
B	$0.23 < WCS \leq 0.50$	3	$0.83 < SCS \leq 1.38$
C	$0.50 < WCS \leq 0.93$	4	$SCS > 1.38$
D	$0.93 < WCS \leq 1.51$		
E	$WCS > 1.51$		

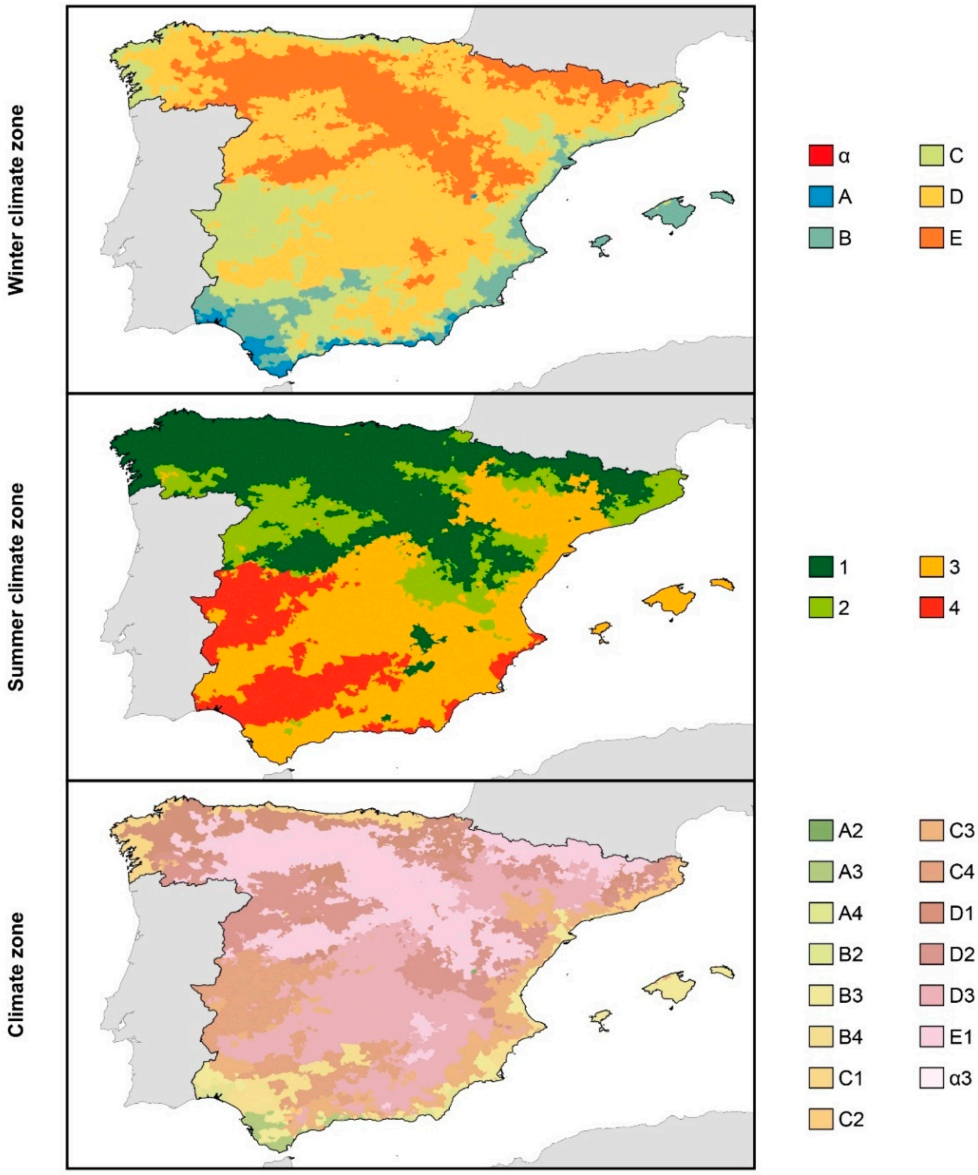

Figure 1. Climate zones from the CTE.

This climate classification determines various aspects related to the energy efficiency. According to the climate zone of the building, limit values are established for the thermal properties of the envelope. This limitation is established by using the thermal transmittance as a regulatory variable. Table 3 indicates the limit values of the thermal properties of the envelope established by the CTE. The establishment of limit values depends on WCZ. The lowest thermal transmittance values are established for the buildings located in the severest climate zones (i.e., those with label E in WCZ).

Table 3. Maximum thermal transmittance values established by the CTE for the building envelope elements.

Element	Maximum Thermal Transmittance (W/(m^{2}K))					
	Winter Climate Zone (WCZ)					
	α	A	B	C	D	E
Wall	0.80	0.70	0.56	0.49	0.41	0.37
Elements in contact with the ground	0.90	0.80	0.75	0.70	0.65	0.59
Roof	0.55	0.50	0.44	0.40	0.35	0.33
Window	3.2	2.7	2.3	2.1	1.8	1.8

2.2. Case Study

A case study was used as an energy model to analyze the effect of varying operational conditions. A case study recently designed according to the demands of the CTE was selected (see Figure 2). The case study was a multifamily building, which was selected because of its importance in the southern European countries. Although stand-alone houses represent around 70% of the European building stock, in southern European countries such as Spain multifamily buildings predominate [47,48]. In other words, most of the population live in these types of buildings. In this regard, data collected by the Spanish government [49] shows that in the last 20 years there have been more dwellings in multifamily buildings (see Figure 2). Furthermore, this case study was the most representative building of the Spanish autonomous communities. Although there were no data on the building typology from the 8131 cities, data from the Spanish autonomous communities were available [49]. Figure 3 shows the percentage distribution of dwellings in each autonomous community according to whether they belong to a stand-alone house or even to a multifamily building. The data showed that, except in the Castilla–La Mancha autonomous community, there were more dwellings in multifamily buildings in all regions. The percentages were greater than 50%, so the representativeness of the case study was ensured in most of the Spanish territory.

The case study had three floors and six dwellings in each. First and second floors had the same distribution, and the distribution of the ground floor was a little bit different, thus reducing its surface slightly (Figure 4). The total surface of the dwellings on the first floor was 329.83 m^2, and the total surface on the ground floor was 318.61 m^2. Table 4 indicates the distribution of the surfaces per rooms in the dwellings located both on the ground floor and on the typical floors (first and second floors). The case study was modelled by DesignBuilder. As the case study was analyzed in various climate zones, the thermal properties of the envelope were adapted to the limit values established by the CTE (see Table 3). A total of six models of the case study were therefore designed (one model per WCZ). Thus, the case study was analyzed according to the requirements established in the CTE for the reference building. This means that the building had the same orientation, size, shape, and use of the rooms in all regions, although the thermal parameters of the envelope were adapted to the limit values established in each climatic zone.

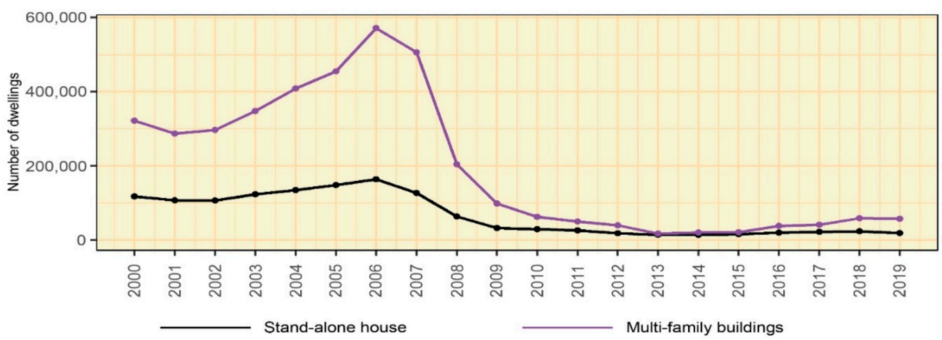

Figure 2. Evolution of dwellings built in Spain from 2000 to nowadays.

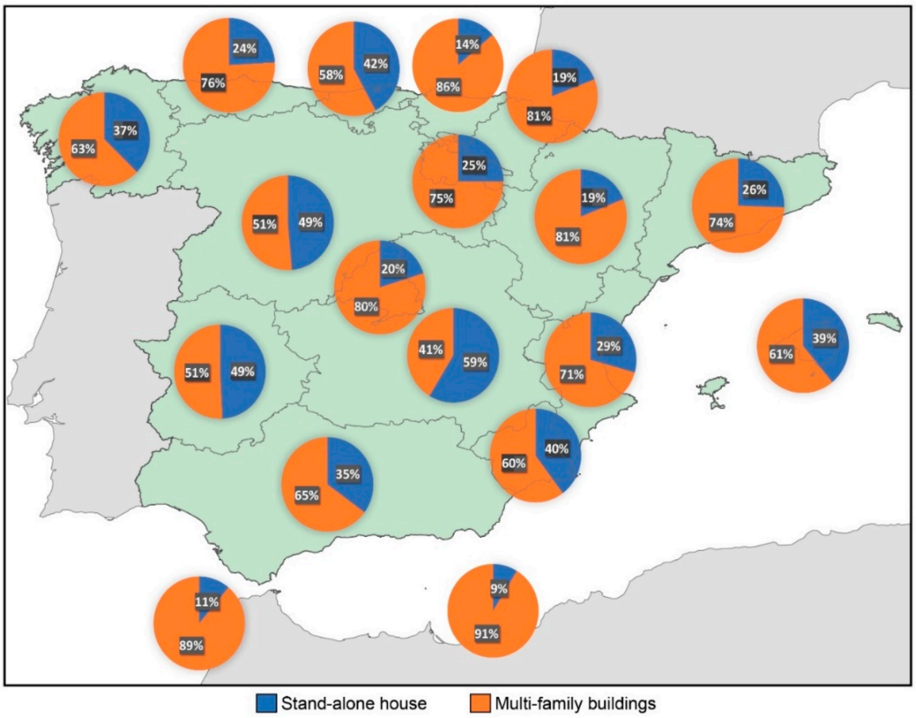

Figure 3. Percentage distribution of the number of dwellings per autonomous community. Data correspond to the dwellings built from 2000 to nowadays.

Figure 4. 3D perspective of the case study and the distribution of the typical floor.

Table 4. Distribution of the surfaces of the dwellings on the ground and typical floor.

Room	Surface (m^2)											
	Ground Floor						First Floor (Typical Floor)					
	A	B	C	D	E	F	A	B	C	D	E	F
LR-K	26.34	27.49	27.46	27.46	27.49	28.98	29.42	27.49	27.46	27.46	27.49	28.99
BR-1	12.15	13.76	12.08	12.08	13.76	12.20	15.65	13.76	12.08	12.08	13.76	12.2
BR-2	8.03	10.85	8.71	8.71	10.85	9.00	9.03	10.85	8.71	8.71	10.85	9.00
BA-1	3.53	3.61	3.34	3.34	3.61	3.78	2.96	3.61	3.34	3.34	3.61	3.73
BA-2	-	-	-	-	-	-	4.25	-	-	-	-	-
Total	50.05	55.71	51.59	51.59	55.71	53.96	61.31	55.71	51.59	51.59	55.71	53.92

LR-K: Living room–kitchen; BR: bedroom; BA: bath.

2.3. Operational Condition Approaches of the Indoor Spaces Analyzed

This study aimed at analyzing the limitations of the operational profile of the CTE established to fulfil the limitations of energy consumption and certification through energy simulation software. A total of three approaches of the operational conditions of HVAC systems were analyzed (see Figure 5):

- Approach 1 corresponded to the residential profile from the CTE. This approach considered a use of the heating systems for the months between October and May, whereas the use of cooling systems corresponded to the summer months. These months coincide with the months corresponding to the calculation of winter and summer climate severities. Regarding the daily use profile, the use varies depending on the system (heating or cooling): the heating system is used throughout the day, whereas the cooling system is not used from 07:00 to 14:59. Indoor setpoint temperatures also vary: (i) as for heating, the indoor setpoint temperature is 20 °C between 7:00 and 22:59, and 17 °C between 23:00 and 6:59; and (ii) as for cooling, the indoor setpoint temperature is 25 ºC between 15:00 and 22:59, and 27 °C between 23:00 and 6:59.
- Approach 2 corresponded to a modification of the residential profile from the CTE. This modification considered that the use of heating and cooling systems is not limited according to the time of year, so that cooling systems could be used in the months considered winter months by the CTE (i.e., October, November, December, January, February, March, April, and May), and the heating systems in summer months (i.e., June, July, August, and September). In such way, it is possible to verify if there is a heating or cooling energy demand in those months in which the CTE considered their use not suitable. Regarding the daily use profile, the same as that used in the residential profile from the CTE was applied.
- Approach 3 corresponded to a modification of the residential profile used in Approach 2. In this case, the criterion of using heating and cooling systems throughout the year was the same. The modification takes place in the daily profile of cooling systems. A daily profile is used to use the cooling system between 07:00 and 14:59, with an indoor setpoint temperature of 25 °C for cooling.

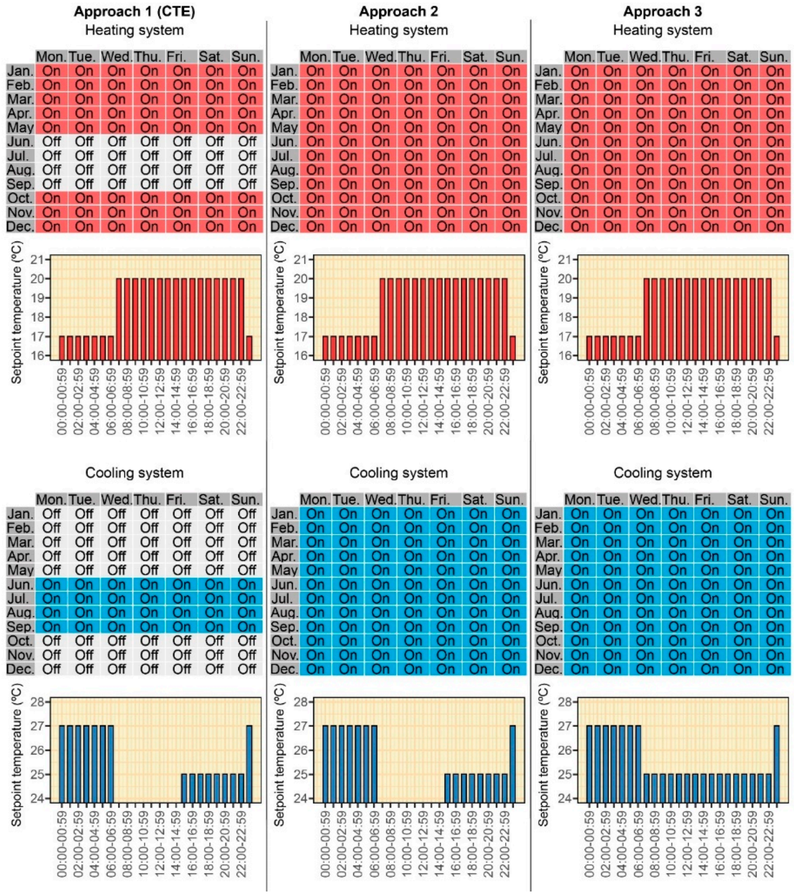

Figure 5. Approaches for the operational conditions of the indoor spaces of the case study.

2.4. Energy Simulation Procedure

This subsection describes the energy simulation procedure. The case study used in this research adopted the values of the thermal properties of the envelope to the limit values established by the CTE for each WCZ, so six models were designed. Likewise, the case study was analyzed by using the three approaches of use conditions of the HVAC systems described in Section 2.3. The HVAC system followed the criterion established by the CTE to define the HVAC system in energy simulation processes: an individual natural gas boiler and radiators with a Coefficient of Performance (COP) of 0.92 were used for heating, and a heat pump with an Energy Efficiency Ratio (EER) of 2.60 was used for cooling.

Regarding the load profile, the profile defined by the CTE for a residential use was applied (see Figure 6). The occupancy of the case study varied depending on the day: from Monday to Friday, the occupancy sensible load varied between 0.54 and 2.15 W/m^2 (with a load of 2.15 W/m^2 all day on weekends), and the occupancy latent load varied between 0.34 and 1.36 W/m^2 (with a load of 1.36 W/m^2 all day on weekends). The load from both lighting devices and systems had the same use profile, which varied between 0.44 and 4.40 W/m^2, depending on the hour of the day.

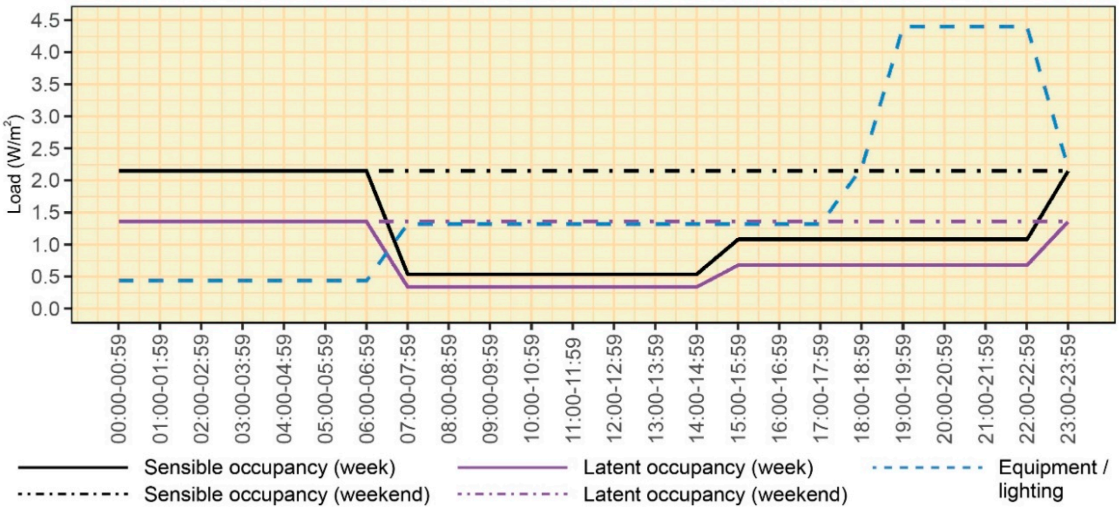

Figure 6. Load profiles from the CTE used in this research.

The case study was also analyzed in the 8131 Spanish cities. For this purpose, the EnergyPlus weather (EPW) files of each city were obtained by using METEONORM, which obtains the EPW of any location through a stochastic process [50]. The coordinates of the cities were obtained from the National Geographic Information Center in Spain [51]. To generate the EPW, the temperature period between 2001 and 2009 was chosen, as well as the radiation period between 1991 and 2010.

The simulation process was conducted with the calculation engine EnergyPlus v 8.9.0. As the variations of the operational conditions of HVAC systems also varied the energy demand of the building, the analysis of results was focused on that variable. As each case study was analyzed in the 8131 Spanish cities and three different operational approaches were used, the results were based on 24,393 simulations. It should be emphasized that this study had several limitations in relation to HVAC systems and their technical characteristics. First, the HVAC systems were adapted to the criteria established in the CTE to perform energy analyses. This means that HVAC systems were not designed with performance improvement devices, such as the outdoor temperature reset control or the heat recovery system. Second, the evaluation of the performance of HVAC systems throughout their useful life was not considered. Finally, this study only analyzed the energy demands for heating and cooling, so the demand for domestic hot water was not analyzed.

3. Results and Discussion

3.1. The Effect of Increasing Calendars to Use HVAC Systems (Approach 2)

The new approaches were analyzed progressively. First, the effect of using the approach with respect to Approach 1 was first analyzed, and then the effect of using Approach 3 with respect to Approach 2.

By analyzing the results of Approach 2, the effect of increasing the calendars to use heating and cooling systems increased in turn the cooling annual energy demand, whereas the heating demand did not vary (see Figure 7). The distribution of the annual values of energy demand in the 15 climate zones from the CTE was useful to verify it. The annual values of heating energy demand were the same as those obtained with Approaches 1 and 2. This aspect showed that the increase of calendars to use heating systems did not increase the heating energy demand in any of the climate zones from the CTE, thus proving the effectiveness of using the calendars for heating systems of the residential profile from the CTE, as it provided an accurate knowledge of the heating energy demand. However, the situation was not the same with cooling systems. The increase of the calendar of cooling systems increased the cooling energy demand, with a different tendency according to the climate zone. This aspect can be proved with the quartile values of data distributions (see Table 5). The use of Approach 2 increased between 0.82 and 4.81 kWh/m^2 year in the first quartile (Q1), between 0.37 and 6.14 kWh/m^2 year in the second quartile (Q2), and between 0.58 and 7.4 kWh/m^2 year in the third quartile (Q3). These increased data implied a percentage deviation rate with respect to Approach 1 between 3.83% and 33.41%. The results obtained by the residential profile from the CTE did not therefore consider between 3.83% and 33.41% of the cooling annual energy demand, which was obtained by using these systems in months not belonging to the summer season. In addition, this percentage deviation could be more stressed in α3 (corresponding to 45 cities of the island territory of the Canary Islands) where the percentage deviation ranged between 49.44% and 53.01%.

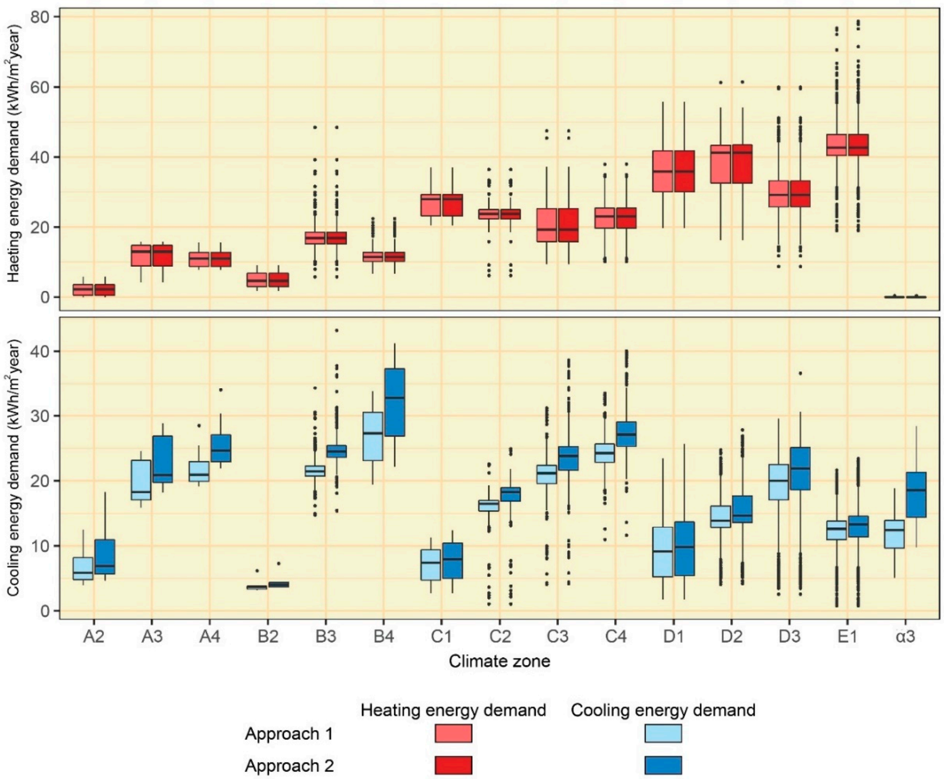

Figure 7. Comparison of the annual distributions of heating and cooling energy demand obtained by Approaches 1 (residential profile from the CTE) and 2.

Table 5. Quartile values obtained by the cooling energy demand from Approaches 1 and 2.

Climate Zone	Cooling Energy Demand (kWh/m^2 Year)					
	Approach 1			Approach 2		
	Q1	Q2	Q3	Q1	Q2	Q3
A2	4.82	5.83	8.32	5.64	6.89	11.10
A3	17.00	18.26	23.20	19.68	20.88	26.99
A4	19.84	20.93	22.98	22.94	24.63	27.15
B2	3.22	3.68	3.84	3.63	4.05	4.42
B3	20.73	21.47	22.28	23.60	24.49	25.43
B4	23.09	27.28	30.57	26.87	32.73	37.30
C1	4.76	7.38	9.39	4.96	7.93	10.45
C2	15.33	16.46	16.95	16.83	18.24	18.95
C3	19.54	21.16	22.37	21.64	23.82	25.26
C4	22.87	24.25	25.64	25.29	27.11	29.03
D1	5.21	9.13	12.89	5.41	9.82	13.70
D2	12.86	13.83	16.14	13.59	14.62	17.68
D3	17.03	20.03	22.54	18.59	21.88	25.15
E1	10.97	12.6	13.82	11.39	13.28	14.57
α3	9.58	12.42	13.96	14.39	18.56	21.36

Despite this increase, the oscillations of the cooling energy demand had a variable range in the various climate zones. The analysis of WCZ and SCZ resulted in a greater relationship of the impact of the cooling energy demand according to the SCZ. In this regard, the WCZ presented a major oscillation between the quartile values obtained, whereas in the SCZ there was a greater relationship between the increase of the cooling energy demand and the increase of summer climate severity. For this reason, the cooling energy demand obtained in the months not considered in Approach 1 was analyzed according to the SCZ (see Figure 8). The cooling energy demand varied according to the months analyzed, so from November to March, the cooling energy demand was almost null, with some outliers in the distribution of cities analyzed in which there were low values of cooling energy demand. Despite these outliers, not using cooling systems in these months would be representative of the actual needs of buildings. However, there was a different tendency in April, May, and October, as results with high values of energy demand were obtained, with a tendency to increase according to the SCZ of the city. In this regard, in the SCZ 1 the quartiles of distributions were low (Q1 ranged between 0 and 0.72 kWh/m^2, Q2 between 0 and 0.51 kWh/m^2, and Q3 between 0 and 0.72 kWh/m^2), and in the SCZ 4 there were greater values in the quartiles (Q1 ranged between 0.15 and 1.79 kWh/m^2, Q2 between 0.26 and 2.03 kWh/m^2, and Q3 between 0.47 and 2.62 kWh/m^2). Likewise, some outliers obtained maximum values of 4.18 kWh/m^2. These values of cooling energy demand modified the percentage contributions of the heating and cooling energy demand in the total energy demand of each month. Whereas in April, May, and October, the percentage contribution of the heating energy demand was 100% in the residential profile, the increase of the calendar for cooling systems varied the percentage contribution of the heating energy demand (see Figure 9), ranging between 61.50% and 90.25% in April, between 10.04% and 27.56% in May, and between 16.20% and 64.10% in October. The results showed that, in May and October, the greater percentage contribution in the total energy demand was cooling for all SCZs, except October in zones 1 and 2. So, the calendar for the cooling systems of the residential profile from the CTE ignored the possible actual cooling energy demand of the building analyzed.

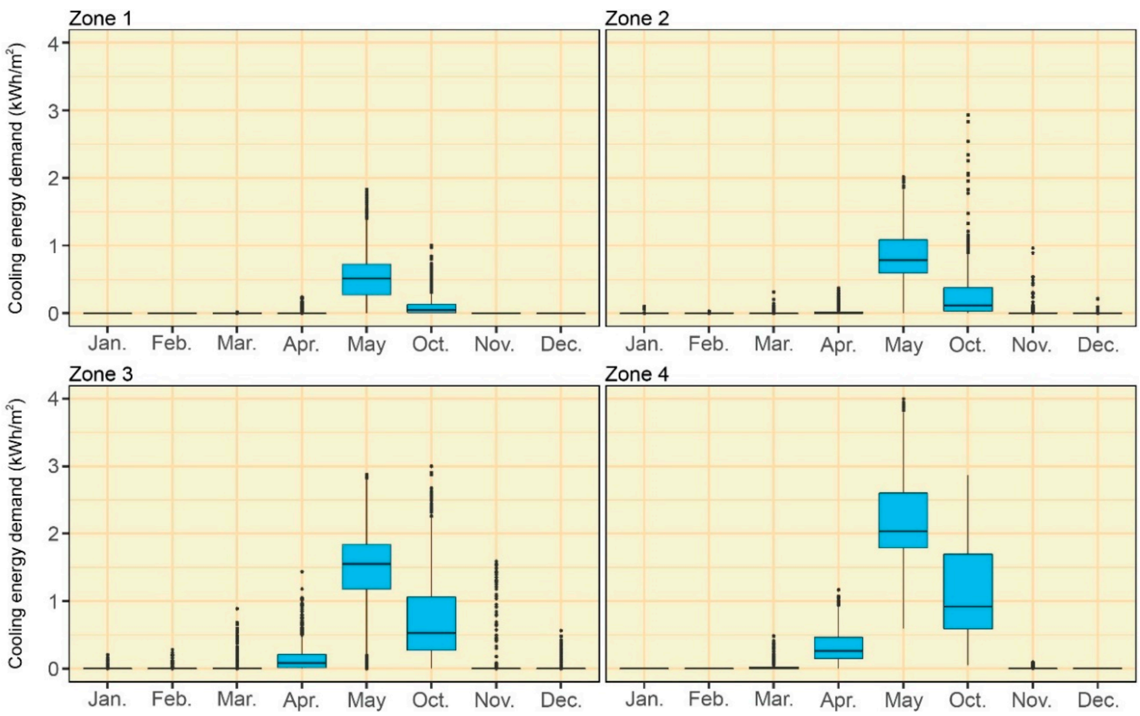

Figure 8. Distributions of the cooling energy demands obtained by Approach 2 in the months not considered by the residential profile from the CTE.

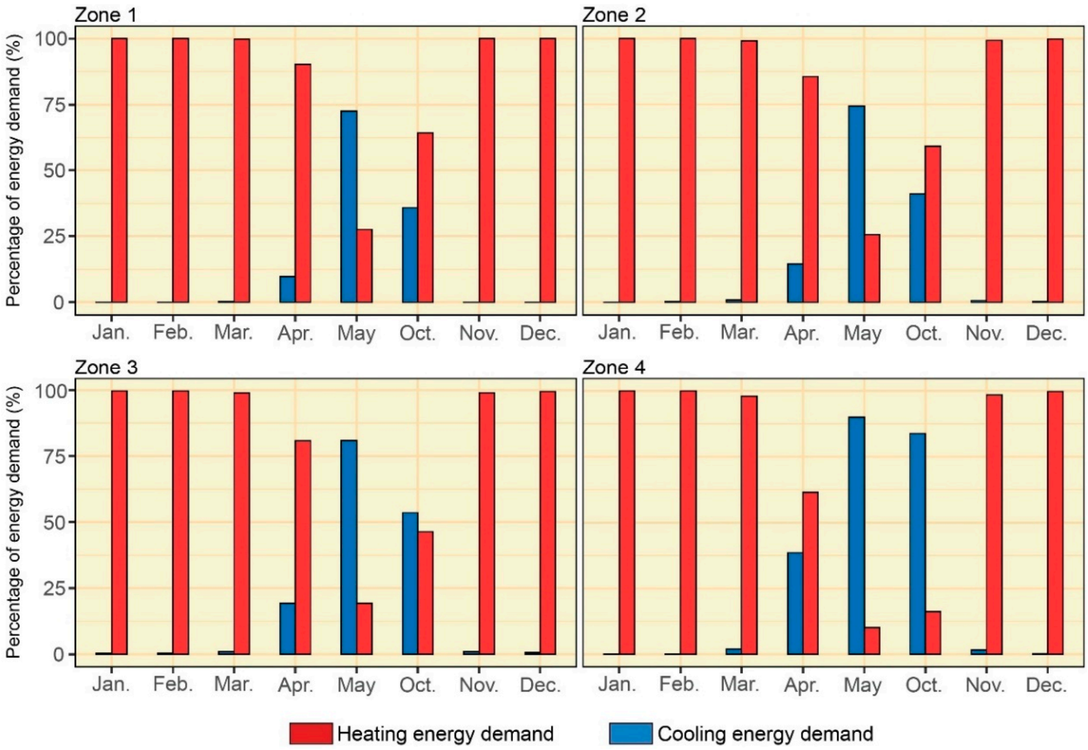

Figure 9. Percentages of the heating and cooling energy demands obtained by Approach 2 in the months not considered by the residential profile from the CTE to use cooling systems (i.e., January, February, March, April, May, October, November, and December).

3.2. Effect of Increasing the Daily Use of Cooling Systems (Approach 3)

The calendar for the use of cooling systems only in summer did not show the actual energy demand of buildings in Spain. However, these results considered that, in the daily use profile of cooling systems, these systems were not used in the hourly range from 07:00 to 14:59, following the criterion established in the residential profile from the CTE. As mentioned in Section 2, another approach to the profile of the operational conditions of HVAC systems was analyzed. In this approach, cooling was also considered from 07:00 to 14:59. The results showed that the use of this hourly range affected the increase of the cooling energy demand, which varied according to the month of the year (see Figure 10): (i) from November to April, the mean increase in all cities was null; and (ii) mean increases of 0.1, 0.48, 0.75, 0.71, 0.35, and 0.03 kWh/m^2 were obtained in May, June, July, August, September, and October, respectively. The months in which the use of cooling systems most influenced from 07:00 to 14:59 were July and August. Likewise, these variations implied a mean variation of the annual cooling energy demand of 2.42 kWh/m^2 year. Nevertheless, these mean increase values in Spain could be affected by the SCZ, so the effect of using them from 07:00 to 14:59 could influence other regions differently. Dispersion graphs show that the deviation with respect to the dispersion diagonal (which would indicate an adjustment among the values obtained by both approaches) is greater for high values of cooling energy demand, whereas for low values, the deviation is almost null.

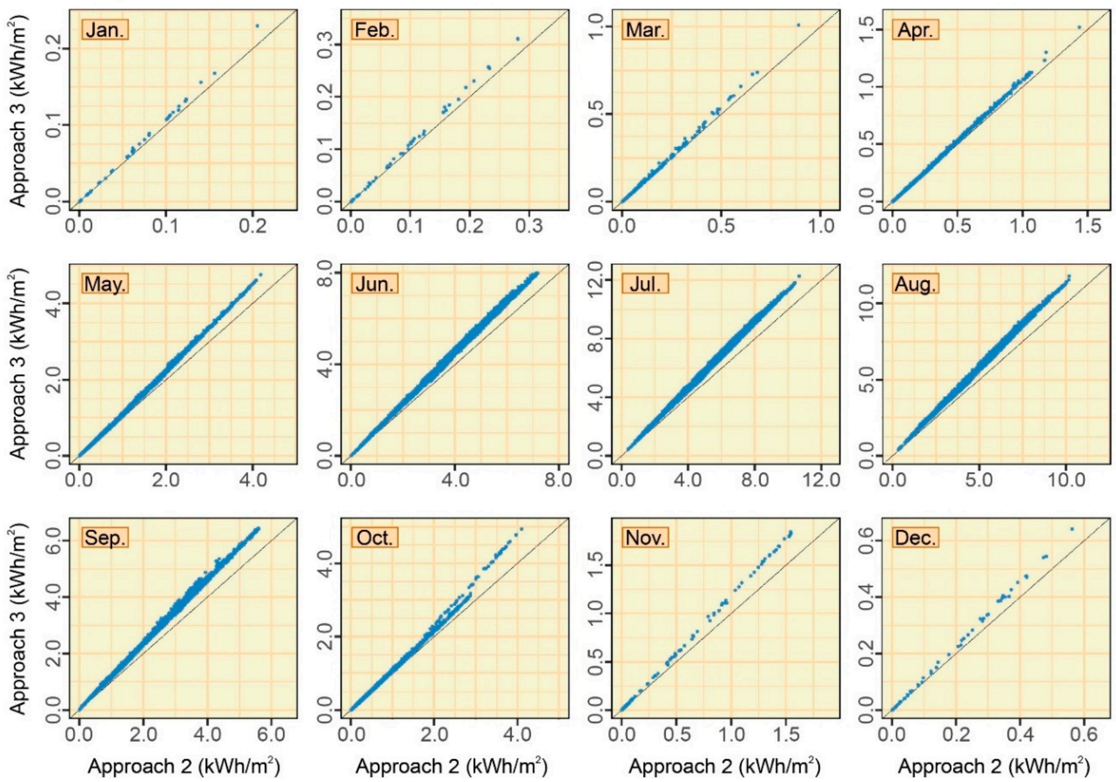

Figure 10. Dispersion diagrams of the monthly values of the cooling energy demand of Approaches 2 and 3. The diagonal corresponding to each plot is represented to visualize the increase better.

For this reason, the results were therefore analyzed according to the SCZ. Figure 11 represents the distributions of the increase of the cooling energy demand obtained by Approach 3 in the SCZ. The SCZ had an important role in the increase value of the cooling energy demand. So, the cities located in the SCZ 1 had low increase values in their distributions (with values of Q1 and Q3 of 0.44 and 0.61 kWh/m^2 in July, and 0.42 and 0.57 kWh/m^2 in August), whereas in the SCZ 4, there was an increase with respect to the SCZ 1 between 0.59 and 0.66 kWh/m^2 year in the quartile values of the summer months. The variation by using the cooling system annually generated a different tendency in the increase of the energy demand according to the summer zone, with values between 0.15 and 6.1 kWh/m^2 year. By analyzing the results per quartiles, there was an increasing tendency of values between Q1 and Q3: between 1.33 and 1.88 kWh/m^2 year in zone 1, between 1.67 and 2.87 kWh/m^2 year in zone 2, between 2.83 and 3.8 kWh/m^2 year in zone 3, and between 3.53 and 4.38 kWh/m^2 year in zone 4.

This increase of the cooling energy demand slightly varied the percentage distributions of cooling and heating energy demand (see Table 6). In this regard, the increases in the percentage contribution of the cooling energy demand ranged between 0% and 0.65% according to the month analyzed. Nonetheless, Table 6 indicates that Approach 3 showed a different reality of the cooling energy demand of the building from that obtained by the residential profile from the CTE. The residential profile from the CTE, as mentioned throughout the paper, considers a contribution of 0% of the cooling energy demand in the months not belonging to summer. However, the results obtained by the increased approaches showed that not using cooling systems is not a realistic aspect. In this regard, the increase of calendars and daily use generated that, in April, May, and October, percentage contributions always greater than 35% were obtained, reaching values of 90.18% in the cities with a greater summer climate severity. These results showed the bias established by the residential profile from the CTE in the energy assessments of buildings, with a strong importance of the heating energy demand to the detriment of the cooling energy demand. Both the fulfilment analysis of the energy efficiency of the CTE (which, according to what the regulation establishes, would guarantee the condition of nearly zero energy consumption buildings) and the analysis of the energy certification of buildings did not completely value the cooling energy consumption. So, an actual knowledge of the buildings designed is not possible, which could set the trend of climate vulnerability of the building stock in future climate change scenarios predicted, in which an increase of the cooling energy demand is predicted [52].

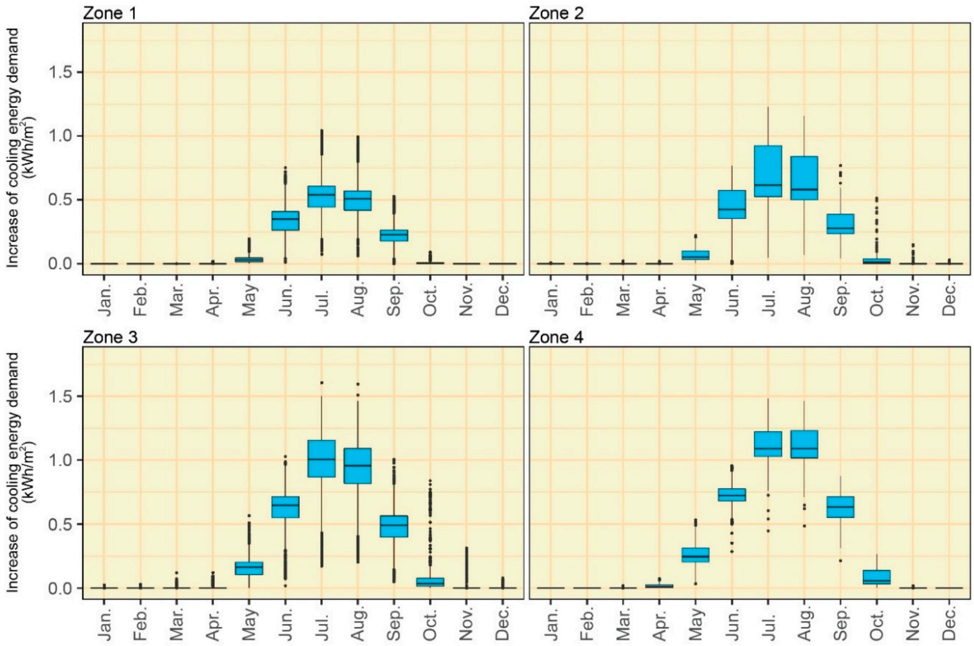

Figure 11. Distributions of the increase values of the monthly cooling energy demand in the summer climate zone (SCZ).

Table 6. Percentage contributions of heating and cooling energy demands of Approaches 2 and 3.

Month	Percentage (%)							
	SCZ 1				SCZ 2			
	Approach 2		Approach 3		Approach 2		Approach 3	
	Heating	Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling
January	100.00	0.00	100.00	0.00	99.97	0.03	99.97	0.03
February	100.00	0.00	100.00	0.00	99.96	0.04	99.96	0.04
March	99.84	0.16	99.84	0.16	99.18	0.82	99.17	0.83
April	90.25	9.75	90.15	9.85	85.49	14.51	85.39	14.61
May	27.56	72.44	26.91	73.09	25.60	74.40	25.00	75.00
June	0.00	100.00	0.00	100.00	0.00	100.00	0.00	100.00
July	0.00	100.00	0.00	100.00	0.00	100.00	0.00	100.00
August	0.00	100.00	0.00	100.00	0.00	100.00	0.00	100.00
September	0.00	100.00	0.00	100.00	0.00	100.00	0.00	100.00
October	64.10	35.90	63.68	36.32	59.05	40.95	58.67	41.33
November	99.98	0.02	99.97	0.03	99.37	0.63	99.34	0.66
December	100.00	0.00	100.00	0.00	99.89	0.11	99.89	0.11
	SCZ 3				SCZ 4			
January	99.62	0.38	99.62	0.38	99.92	0.08	99.92	0.08
February	99.57	0.43	99.57	0.43	99.88	0.12	99.88	0.12
March	98.91	1.09	98.90	1.10	97.91	2.09	97.88	2.12
April	80.77	19.23	80.62	19.38	61.51	38.49	61.28	38.72
May	19.18	80.82	18.70	81.30	10.04	89.96	9.82	90.18
June	0.00	100.00	0.00	100.00	0.00	100.00	0.00	100.00
July	0.00	100.00	0.00	100.00	0.00	100.00	0.00	100.00
August	0.00	100.00	0.00	100.00	0.00	100.00	0.00	100.00
September	0.00	100.00	0.00	100.00	0.00	100.00	0.00	100.00
October	46.40	53.60	45.92	54.08	16.20	83.80	15.81	84.19
November	98.99	1.01	98.97	1.03	98.37	1.63	98.31	1.69
December	99.40	0.60	99.40	0.60	99.72	0.28	99.72	0.28

4. Conclusions

This study analyzed the limitation of the profile of HVAC systems' operational conditions in residential buildings established by the Spanish Building Technical Code for the energy analysis through simulations, which guarantee both the category of nearly zero energy consumption buildings and the energy certification. Based on the study, the following conclusions were drawn:

- The increase of calendars to use heating and cooling systems influenced in different ways. Whereas in the cooling energy demand the increase was almost null in the summer months, in the cooling energy demand there were significant values of cooling energy demand in April, May, and October, and outliers with values of cooling energy demand in the months between November and March. This increase of calendars to use cooling systems varied the heating and cooling percentage contributions in the total energy demand of each month, so the cooling energy demand was the most important in May and October.
- There was also a different tendency of the effect of increasing calendars to use cooling systems according to the summer climate severity. In this regard, SCZ showed a greater influence of the increase of using cooling systems on the increase of cooling energy demand. This aspect showed that the assessment of fulfilling the energy efficiency of buildings according to the Spanish Building Technical Code could imply that, in cities with warm climates, the building energy consumption is greater than that analyzed according to the regulation.
- Also using cooling systems from 07:00 to 14:59 increased the cooling energy demand in all months of the year, although the impact was greater in July and August. The annual energy demand also increased, ranging between 0.15 and 6.1 kWh/m^2 year, according to the climate conditions of the city.

To conclude, the results of this study prove the possible bias of national regulations in assessing the building energy performance. Although previous research studies analyzed the influence of occupancy profiles [18], the operational patterns of HVAC systems also influence the analysis of the building energy performance. Limiting the use of cooling systems implies that there is not an accurate knowledge of the possible energy demand of the building, particularly in the warmest regions. This most important tendency of the heating energy demand therefore shows the limitations of the current regulation as regards energy efficiency in Spain, in which design strategies (such as the envelope design) are based on thermal variables aimed at limiting the heating energy demand. The use of broader operational profiles for cooling systems could lead to the use of design strategies more focused on the alleviation of the cooling energy demand. Also, new future research lines should advance the establishment of operational profiles to analyze various operation hypotheses of residential buildings according to the sociocultural character and users' habits. In this regard, users with a greater thermal adaptability could use resilient strategies, such as natural ventilation or setpoint temperatures with more efficient values. In addition, the Covid-19 pandemic has forced families to remain in their dwellings for a long time. When designing various operational profiles for family units who telework or work outside the dwelling, it would be useful to know the building energy performance during confinement episodes. The design of new operational profiles would therefore allow the state regulation to establish various efficient design strategies for buildings. Finally, the characteristics of HVAC systems (e.g., the outdoor temperature reset control) and the modification of their performance throughout their lives should be evaluated in future works to know the limitations associated with the characteristics of HVAC systems considered in the energy simulation processes of Spanish regulations.

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