Title:

Analysing the inequitable energy framework for the implementation of nearly zero energy buildings (nZEB) in Spain

Abstract

Most countries from the European Union work towards a low-carbon horizon in the building sector. As for Spain, the last modification of the Spanish Building Technical Code in 2020 establishes that every building ensuring the fulfilment of the regulation will obtain the category of nearly zero energy building. However, the limit values of the thermal properties of envelopes only distinguish 6 variations according to the winter climate zone. For this reason, this study analyses the potential risk of the existence of energy inequalities due to the fulfilment of the regulation as regards energy efficiency in Spain. A total of 48,786 energy simulations were performed by taking the 8,131 municipalities of the country into account, as well as the previous and current regulation. The results considered heating and cooling demands, cluster analyses, and their impact on population, showing that the improvement of thermal properties could guarantee buildings with a better energy performance for a greater number of inhabitants. There was, however, a limitation in the current climate classification, so a more detailed climate classification with new limit values is required. The results also showed the limitations of use of the thermal transmittance to reduce the cooling energy consumption. This study could be the starting point to establish new regulatory parameters to reduce energy consumption equitably, considering the importance of cooling consumption in future climate change scenarios.

Highlights

- A total of 48,786 energy simulations taking the 8,131 cities of Spain into account.
- Cluster analyses based on heating and cooling energy demand.
- Energy inequalities detected in buildings in the same climate zone.
- The Spanish regulation from 2020 guarantees more efficient buildings.

Keywords

Nearly zero energy building; energy efficiency; Spanish Building Technical Code; Energy inequalities; Building performance simulation

1. Introduction

The mitigation of global warming constitutes one of the main goals of the 21st century as the temperature increase of the planet would impact on habitability conditions. According to the Intergovernmental Panel on Climate Change (IPCC), expected changes in climate could seriously affect the liveability on the planet [1,2], including the extinction of species, glaciers, and cities close to the coast. This situation mainly arises from the high greenhouse gas emissions (GHG) generated by anthropogenic activities. The high building energy consumption is among these activities due to the deficient energy behaviour of most of the existing building stock [3–6]. This aspect has been reflected in quantified energy consumption data in various regions. As for the European Union, building stock was responsible for 40% of the annual energy consumption [7,8] and 36% of annual GHG emissions [9,10] in the continent.

In this context the European Union is devising a legal framework to achieve a low carbon economy for 2050 [11] by reducing GHG emissions in sector such as the industry, transport or building sector, for which the European Union aims at a reduction of GHG emissions by 90%. The recent Directive 2018/844 [12] set the need for European countries to develop energy renewal strategies of the existing building stock to make it energy-efficient by 2050. Energy demand for cooling and heating in buildings strongly depends on their envelope, thus strategies aiming at reducing that demand specifically target this element [13–16]. A considerable number of studies have highlighted the importance of the building envelope in containing or reducing the energy demand for heating and cooling in different contexts. Sarkar and Bose [17] analysed the effect of improving the thermal properties of the envelope of buildings located in India. Savings between 40% and 60% in heating energy demand and between 25% and 40% in cooling energy demand were obtained; Tsikaloudaki et al. [18] evaluated how the thermal properties of windows affect the cooling demand of residential and office buildings in Rome, Malaga, Lisbon, Larnaca, and Athens, and the study concluded that an optimal combination of those properties allows for a reduction of up to 70% of the demand in both typologies A study conducted in extant educational buildings in Jordan clarified that adding insulation to the walls and roofs as part of a retrofitting process can lead to savings of 59% and 36% in the cooling and heating demand respectively [19]. Similar conclusions were obtained by a study on higher educational buildings in Hangzhou (China); a combination of different optimization strategies, among which lower U values of the building envelope are included, led to savings of 46% for cooling loads and 39% for heating loads [20]. A parametric study conducted in several Italian cities highlighted that a lower window-to-wall ratio (WWR) leads to lower cooling and heating consumption, provided that other parameters, such as internal loads or thermal transmittance of walls, are kept within controlled ranges [21]. López-Mesa et al. [22] clarified how energy efficient retrofit strategies can lead to relevant energy savings in the heating demand; the case study comprising 3 blocks without heating insulation in a residential housing complex showed that heating demand could be reduced from 67 kW/hm^{2}year to around 2.85 kW/hm^{2}year in the best case scenario, but in this case cooling demand, despite being much lower in the base case scenario, was not significantly reduced. Another study conducted in an educational building in Canada focused on how higher U-values in the basement's walls and lower heat losses are directly correlated, being the latter reduced up to 60% [23]. Significant reductions can be also be seen in new buildings, as proved by the study of Echarri-Irribarren et. al [24]; the energy demand for cooling and heating was assessed for three different energy standards in Spain, and it was concluded that the cooling demand could be reduced up to 72% and the heating demand up to 67% if the passive house standard is applied. Another similar study conducted in residential buildings located in four cities of Turkey clarified that the insulation thickness can be optimized to contain both the heating and cooling demand. As a result, heating demand can be reduced around 90% and cooling demand around 92% when an optimal combination of thickness and materials is used ~~[25]~~. Significant reductions of around 50%, this time in the heating demand, are observed according to the study by Braulio-Gonzalo and Bovea [26], who adopted a similar approach, aiming at optimizing the insulation thickness to contain the energy demand. These two studies included also insightful considerations about other aspects, such as life cycle of materials and payback period of the necessary economic investment.

The authors have also conducted several studies on this topic, shedding light on different strategies for energy-savings in buildings. When talking about the external envelope, thermal bridges also play an important role in reducing the energy demand; a recent study by Bienvenido-Huertas et al. [27] concluded that a reduction in the linear transmittance of front slabs may reduce the heating energy demand by 18% and the cooling demand by 3%. Other studies have also supported this claim, arguing that it is of uttermost importance to include thermal bridges in the calculation model and to reduce its thermal transmittance; cooling energy demand was reduced between 33%-66% but results for the heating demand were inconclusive after analysing different insulation strategies for buildings in Brazil [28]. On top of that, the authors have also started to explore the possibilities of considering dynamic thermal properties as part of the energy-saving strategies, and a recent study clarified that not only U-values, but also time shift and decrement factor are essential to contain optimize the energy performance of the buildings located in different climates of Spain.

However, when it comes to energy savings, one should not forget the particularities of the building industry, which is usually labelled as inefficient and low productive [29]. Regarding the legislative framework on energy efficiency, this implies that buildings are insulated as per the minimum limits set by the standards. Within the Spanish context, the first regulation on this matter was enacted in 1.979, a few years after the oil crisis of 1.973, included basic limitations for the U-value of the thermal envelope [30] and remained in force for 27 years. In 2006, following the guidelines of the EU, a new Technical Building Code was enacted; stricter limits for the U-values, as well as complex calculation procedures that included computer software were introduced [31]. In 2.020, the European directive 2010/31/UE [10] was a great breakthrough, and stablished the bases for adapting the concept of nearly zero energy building (nZEB) to the national regulations. In response to that, the Spanish CTE underwent heavy modifications to accommodate the nZEB standard into its legislative framework.

The current version Spanish CTE stablishes limit values for the thermal transmittance of the external envelope based primarily on the climate zone where the building is located, in the same way as the regulation in other countries; every Spanish province is assigned to a climate zone, and then the limits are tuned depending on the altitude of the given municipality. This approach, though easy to grasp, may lead to inequalities among provinces, as a former study concluded [32]. The background research has pointed out that lowering the limits for the U-values may bring significant reductions in the heating and the cooling demand, whereas it may be difficult to balance both of them, especially in climates with ample thermal oscillations between summer and winter. The implementation of the nZEB standards into the Spanish CTE represents a radical change in the standards for building insulation, thus an opportunity arises to rethink the approach towards climate classification. Some authors, such as Attia et al. [33], have already pointed out the difficulties in implementing this standard in warm climates, while others call attention on the implications that this may have in reducing the energy expenditure of deprived households [34,35] and the resilience of the building industry towards climate change [36].

Given this context, the authors consider that there is a need for further research on this topic, since the implementation of the nZEB standard into the Spanish framework is very recent and the climate classification remains outdated and based on a provincial division. For that purpose, this study aims at clarifying the inequalities that the implementation of the nZEB standard may bring within the actual climate zones, thus proposing a new classification based on clusters that group the 8.131 Spanish municipalities. The inequalities will be gauged using the expected cooling and heating demand, which will be analysed in two scenarios: Considering the current version of the Spanish CTE and the future implementation of the nZEB standard. According to the background literature on this topic, it is hypothesized that great inequalities may arise, especially when considering both demands separately. This study bring novelty to the field in discussing the theoretical basis of the current climate zoning, and also introduces innovative computer-based calculation procedures that can handle large amounts of data and deliver results based in a robust and reliable analysis. The results of this study will be of use for the future versions of the Spanish building code, which calls for a new climate zoning specifically suited to the needs of a restrictive standard; moreover, this research aims at stablishing also a methodological framework that can be extrapolated to other countries.

2. Methodology

2.1. Climate zones in Spain and the limit values established for the envelope

The territorial organisation of Spain is based on autonomous regions, provinces, and municipalities, in descending size order. Municipalities are the equivalent to the cities of Spain. The total number of municipalities in Spain is 8,131 (see Figure 1). To establish the requirements as regards energy efficiency, new and restored buildings should follow the criteria set by the Spanish Technical Building Code (CTE) [37]. Requirements are usually established based on the climate zone in which the building is located. For this purpose, the climate classification included in the CTE is used. This climate classification uses the concepts of winter climate severity (WCS) (see Eq. (1)) and summer climate severity (SCS) (see Eq. (2)).

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

$$SCS = 2.990 \cdot 10^{-3} \cdot DD_S - 1.1597 \cdot 10^{-7} \cdot DD_S^2 - 1.713 \cdot 10^{-1} \tag{2}$$

Where DD_W and DD_S is the mean degree days based on 20 ºC in winter and in summer, respectively; $\frac{n}{N}$ is the ratio between the numbers of hours of sun (n) and the maximum number of hours of sun (N) in Winter.

Each municipality is classified based on the value of WCS and SCS obtained. For WCS, a letter between A and E is assigned, and for SCS, a number between 1 and 4 (see Table 1). The combination of WCS and SCS obtains 12 climate zones. For the correct climate classification, the CTE identifies the climate zone of each city according to its altitude (see Table 2), thus identifying the 8,131 municipalities of Spain in detail (see Figure 2).

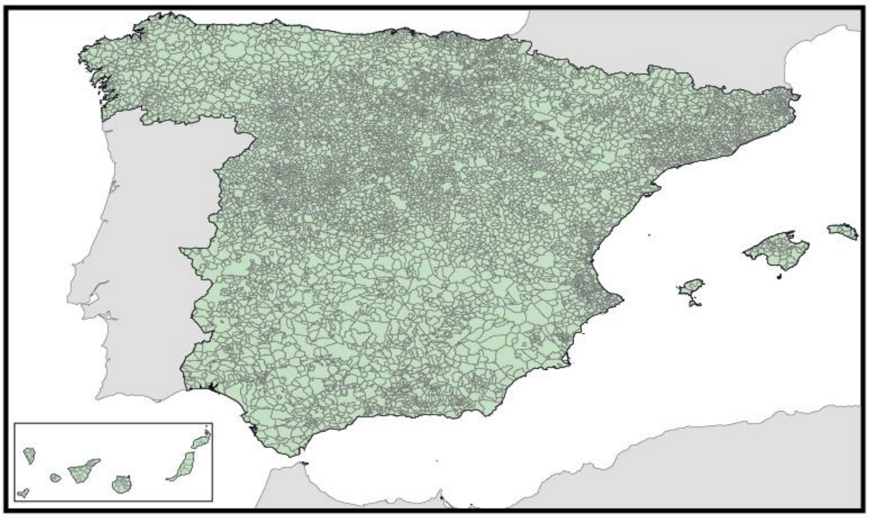

Figure 1. Distribution of the 8,131 Spanish municipalities.

Table 1. Classification intervals for WCS and WCS.

WCS		SCS	
Category	Value	Category	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	$WCS > 1.51$		

Table 2. List of climate classification per altitude above the sea level and province.

<table>
<tr><th rowspan="2">Province</th><th colspan="23">Altitude above the sea level [m]</th></tr>
<tr><th>≤ 50</th><th>51 - 100</th><th>101 - 150</th><th>111 - 200</th><th>201 - 250</th><th>251 - 300</th><th>301 - 350</th><th>351 - 400</th><th>401 - 450</th><th>451 - 500</th><th>501 - 550</th><th>551 - 600</th><th>601 - 650</th><th>651 - 700</th><th>701 - 750</th><th>751 - 800</th><th>801 - 850</th><th>851 - 900</th><th>901 - 950</th><th>951 - 1000</th><th>1001 - 1050</th><th>1051 - 1250</th><th>1251 - 1300</th><th>≥ 1301</th></tr>
<tr><td>Albacete</td><td colspan="9">C3</td><td colspan="10">D3</td><td colspan="4">E1</td></tr>
<tr><td>Alicante</td><td colspan="4">B4</td><td colspan="10">C3</td><td colspan="9">D3</td></tr>
<tr><td>Almeria</td><td colspan="2">A4</td><td colspan="2">B4</td><td colspan="3">B3</td><td colspan="8">C3</td><td colspan="8">D3</td></tr>
<tr><td>Alava</td><td colspan="12">D1</td><td colspan="11">E1</td></tr>
<tr><td>Asturias</td><td>C1</td><td colspan="10">D1</td><td colspan="12">E1</td></tr>
<tr><td>Avila</td><td colspan="11">D2</td><td colspan="6">D1</td><td colspan="6">E1</td></tr>
<tr><td>Badajoz</td><td colspan="8">C4</td><td>C3</td><td colspan="14">D3</td></tr>
<tr><td>Baleares</td><td colspan="4">B3</td><td colspan="19">C3</td></tr>
<tr><td>Barcelona</td><td colspan="4">C2</td><td colspan="4">D2</td><td colspan="6">D1</td><td colspan="9">E1</td></tr>
<tr><td>Bizkaia</td><td colspan="4">C1</td><td colspan="19">D1</td></tr>
<tr><td>Burgos</td><td colspan="12">D1</td><td colspan="11">E1</td></tr>
<tr><td>Caceres</td><td colspan="12">C4</td><td colspan="9">D3</td><td colspan="2">E1</td></tr>
<tr><td>Cadiz</td><td colspan="3">A3</td><td colspan="6">B3</td><td colspan="3">C3</td><td colspan="5">C2</td><td colspan="6">D2</td></tr>
<tr><td>Cantabria</td><td colspan="3">C1</td><td colspan="10">D1</td><td colspan="10">E1</td></tr>
<tr><td>Castellon</td><td colspan="2">B3</td><td colspan="8">C3</td><td colspan="2">D3</td><td colspan="8">D2</td><td colspan="3">E1</td></tr>
<tr><td>Ceuta</td><td colspan="23">B3</td></tr>
<tr><td>Ciudad Real</td><td colspan="9">C4</td><td>C3</td><td colspan="13">D3</td></tr>
<tr><td>Cordoba</td><td colspan="3">B4</td><td colspan="8">C4</td><td colspan="12">D3</td></tr>
<tr><td>Coruña</td><td colspan="4">C1</td><td colspan="19">D1</td></tr>
<tr><td>Cuenca</td><td colspan="16">D3</td><td colspan="5">D2</td><td colspan="2">E1</td></tr>
<tr><td>Gipuzkoa</td><td colspan="8">D1</td><td colspan="15">E1</td></tr>
<tr><td>Girona</td><td colspan="2">C2</td><td colspan="10">D2</td><td colspan="11">E1</td></tr>
<tr><td>Granada</td><td>A4</td><td colspan="6">B4</td><td colspan="5">C4</td><td colspan="4">C3</td><td colspan="6">D3</td><td>E1</td></tr>
<tr><td>Guadalaja</td><td colspan="19">D3</td><td>D2</td><td colspan="3">E1</td></tr>
<tr><td>Huelva</td><td>A4</td><td colspan="2">B4</td><td colspan="4">B3</td><td colspan="9">C3</td><td colspan="7">D3</td></tr>
<tr><td>Huesca</td><td colspan="4">C3</td><td colspan="4">D3</td><td colspan="6">D2</td><td colspan="9">E1</td></tr>
<tr><td>Jaen</td><td colspan="7">B4</td><td colspan="8">C4</td><td colspan="7">D3</td><td>E1</td></tr>
<tr><td>Leon</td><td colspan="23">E1</td></tr>
<tr><td>Lleida</td><td colspan="2">C3</td><td colspan="10">D3</td><td colspan="11">E1</td></tr>
<tr><td>Lugo</td><td colspan="10">D1</td><td colspan="13">E1</td></tr>
<tr><td>Madrid</td><td colspan="10">C3</td><td colspan="9">D3</td><td>D2</td><td colspan="3">E1</td></tr>
<tr><td>Malaga</td><td colspan="2">A3</td><td colspan="4">B3</td><td colspan="8">C3</td><td colspan="9">D3</td></tr>
<tr><td>Melilla</td><td colspan="23">A3</td></tr>
<tr><td>Murcia</td><td colspan="2">B3</td><td colspan="9">C3</td><td colspan="12">D3</td></tr>
<tr><td>Navarra</td><td colspan="2">C2</td><td colspan="5">D2</td><td colspan="5">D1</td><td colspan="11">E1</td></tr>
<tr><td>Ourense</td><td colspan="3">C3</td><td colspan="3">C2</td><td colspan="10">D1</td><td colspan="7">E1</td></tr>
<tr><td>Palencia</td><td colspan="16">D1</td><td colspan="7">E1</td></tr>
<tr><td>Palmas</td><td colspan="7">α3</td><td colspan="8">A2</td><td colspan="5">B2</td><td colspan="3">C2</td></tr>
<tr><td>Pontevedra</td><td colspan="7">C1</td><td colspan="16">D1</td></tr>
<tr><td>Rioja</td><td colspan="4">C2</td><td colspan="10">D2</td><td colspan="9">E1</td></tr>
<tr><td>Salamanca</td><td colspan="17">D2</td><td colspan="6">E1</td></tr>
<tr><td>Segovia</td><td colspan="21">D2</td><td colspan="2">E1</td></tr>
<tr><td>Seville</td><td colspan="4">B4</td><td colspan="19">C4</td></tr>
<tr><td>Soria</td><td colspan="4">B4</td><td colspan="19">C4</td></tr>
<tr><td>Tarragona</td><td colspan="2">B3</td><td colspan="8">C3</td><td colspan="13">D3</td></tr>
<tr><td>Tenerife</td><td colspan="7">α3</td><td colspan="8">A2</td><td colspan="5">B2</td><td colspan="3">C2</td></tr>
<tr><td>Teruel</td><td colspan="9">C3</td><td>C2</td><td colspan="10">D2</td><td colspan="3">E1</td></tr>
<tr><td>Toledo</td><td colspan="10">C4</td><td colspan="13">D3</td></tr>
<tr><td>Valencia</td><td>B3</td><td colspan="9">C3</td><td colspan="9">D2</td><td colspan="4">E1</td></tr>
<tr><td>Valladolid</td><td colspan="16">D2</td><td colspan="7">E1</td></tr>
<tr><td>Zamora</td><td colspan="16">D2</td><td colspan="7">E1</td></tr>
<tr><td>Zaragoza</td><td colspan="4">C3</td><td colspan="9">D3</td><td colspan="10">E1</td></tr>
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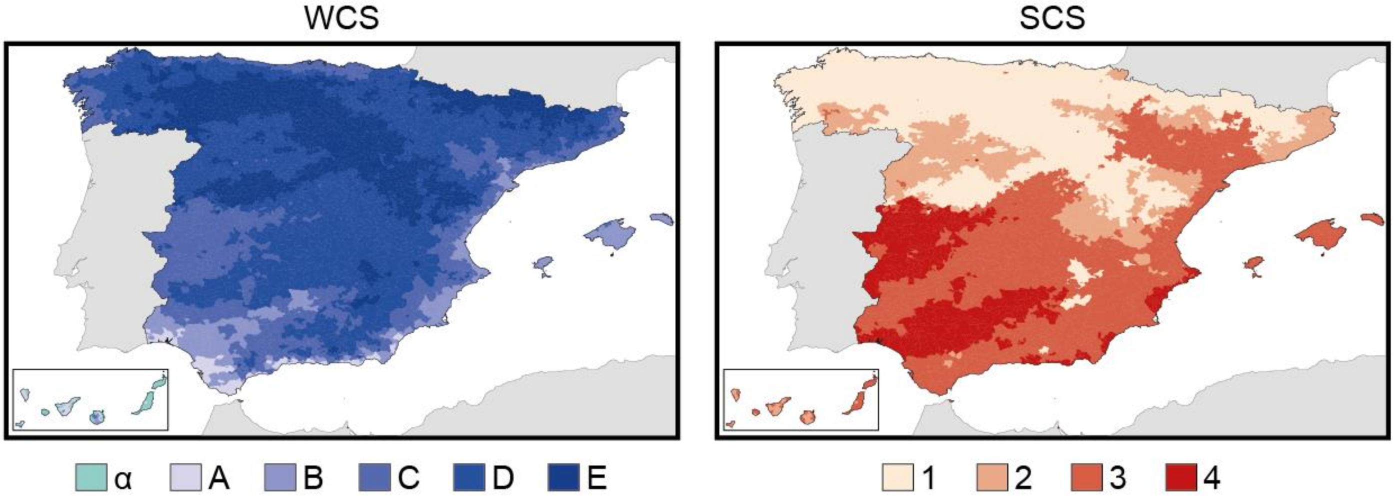

Figure 2. Winter and summer climate severity in Spanish municipalities.

The thermal characteristics of the building envelope are regulated by the CTE. For this purpose, maximum values of thermal transmittance (U-value) are established for different envelope elements based on the winter climate severity. From 2006 to 2019, the limit values established were those included in Table 3. However, a recent modification of the CTE determines more restrictive U-value of the envelope elements (see Table 4), in accordance with the goals of achieving a nearly zero energy consumption in new or restored buildings. In this regard, walls are where the U-values are more restricted, with percentage reductions ranging between 32 and 44%, whereas in roofs, there is a high reduction in one of the climate zones (54% in zone α), and in the other zones, medium percentage reductions (between 20 and 38%) turn into low percentage reductions (between 6 and 13%).

Table 3. Limit U-values of building envelope (CTE until 2019).

Element	Maximum U-value [W/(m^{2}K)]					
	Winter climate severity					
	α	A	B	C	D	E
Wall	1.35	1.25	1.00	0.75	0.60	0.55
Wall or slab in contact with the ground	1.35	1.25	1.00	0.75	0.60	0.55
Party wall	1.35	1.25	1.10	0.95	0.85	0.70
Roof	1.20	0.80	0.65	0.50	0.40	0.35
Floor in contact with the air	1.20	0.80	0.65	0.50	0.40	0.35
Window	5.70	5.70	4.20	3.10	2.70	2.50

Table 4. Limit U-values of building envelope (CTE since 2020).

Element	Maximum U-value [W/(m^{2}K)]					
	Winter climate severity					
	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
Party wall	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
Floor in contact with the air	0.80	0.70	0.56	0.49	0.41	0.37
Window	3.2	2.7	2.3	2.1	1.8	1.8

2.2. Case studies

Three case-studies, which are representative of common residential typologies in Spain, were analysed. These are representative typologies in terms of dwelling types, compactness, dwelling area and external envelope, and the necessary data to model them was extracted from the report of building construction, which is published every 4 years by the Spanish Ministry of Public Works; the latest on-line available edition, which covers the period 2013-2017, was chosen for this study [38]

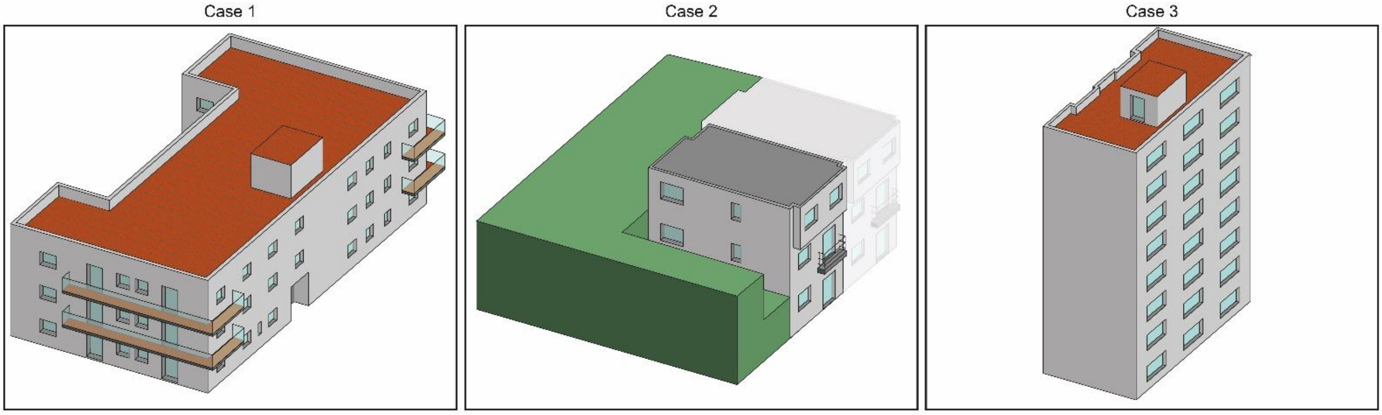

Figure 3. Case studies.

The case studies were modelled and simulated with EnergyPlus v9.1. The models were validated according to the ASHRAE Guideline 14-2014 [39]. For this, measurements of the external and internal air temperature were carried out in a similar way to that carried out in other works [40,41] and it was verified that the values obtained with the statistical parameters of the Mean Bias Error and of the Coefficient of Variation of the Root Mean Square Error were lower than 10 and 30%, respectively. For simulations, designs of the case studies adapted to the limit values of each climate zone were used. For this purpose, the surface of indoor spaces was aimed to not be affected by the variations of the values of the thermal transmittance (e.g., a lower thermal transmittance value could be obtained by increasing the thickness of the thermal insulating, thus increasing the thickness of the wall and reducing the surface of the dwelling). So, a wall of only one layer was defined in each case study whose thermal transmittance was equivalent to that obtained by a multilayer wall. In each building solution, the equivalent thermal conductivity was determined according to the thickness of the wall and the limit thermal transmittance defined in Tables 3 and 4 (see Eq. (3)). A total of 12 designs were defined in each case study: 6 designs by adapting the thermal properties of the envelope to the limit values established by the regulation recently repealed (see Table 3) and other 6 designs by adapting the thermal properties to the new limit values (see Table 4). So, 36 designs were defined. Each design of the case studies was simulated in the municipalities of the respective climate zone (e.g., the design of the case study 1 for the climate zone A was only simulated in the municipalities which belong to the climate zone A). The results of this research are therefore based on 48.786 energy simulations.

$$\lambda_{eq} = \frac{s}{\frac{1}{U} - Rsi - Rse} \tag{3}$$

Where λ_{eq} is the equivalent thermal conductivity [W/mK]; s is the thickness of the element [m]; U is the limit value of thermal transmittance established in the regulation; Rsi and Rse are the internal and external surface thermal resistances obtained through ISO 6946 according to the direction of the heat flux [m^{2}K/W].

As for the load profile, the profile defined in the CTE for a residential use was used (see Table 5). The occupancy of the case study varies depending on the day: from Monday to Friday, between 0.54 and 2.15 W/m^2, and the occupancy in weekends is 2.15 W/m^2. The load both from lighting devices and equipment has the same usage profile, which varies depending on the hour of the day between 0.44 and 4.40 W/m^2.

Table 5. Hourly distribution of the loads in the case study.

Loads		Time period					
		0:00 – 6:59	07:00 – 14:59	15:00 – 17:59	18:00 – 18:59	19:00 – 22:59	23:00 – 23:59
Sensible load (W/m²)	Weekdays	2.15	0.54	1.08	1.08	1.08	2.15
	Weekend	2.15	2.15	2.15	2.15	2.15	2.15
Latent load (W/m²)	Weekdays	1.36	0.34	0.68	0.68	0.68	1.36
	Weekend	1.36	1.36	1.36	1.36	1.36	1.36
Lighting (W/m²)	Weekdays and weekend	0.44	1.32	1.32	2.20	4.40	2.20
Equipments (W/m²)	Weekdays and weekend	0.44	1.32	1.32	2.20	4.40	2.20

For setpoint temperatures, the values defined in the residential profile of the Spanish regulation was also used (see Table 6). These setpoint temperatures are based on a static thermal comfort model in which users' thermal expectations do not depend on the external conditions. A period to use heating equipment is established between October and May, as well as a period to use air conditioning equipment between June and September. These periods to use HVAC systems coincide with the periods established in the calculation of WCS and SCS. Likewise, according to the hour of the day, there are two types of setpoint temperature.

Table 6. Setpoint temperatures used in the case studies.

Setpoint temperature	Months	Time period			
		0:00 – 6:59	07:00 – 14:59	15:00 – 22:59	23:00 – 23:59
Heating setpoint temperature	January – May	17	20	20	17
	June – September	-	-	-	-
	October - December	17	20	20	17
Cooling setpoint temperature	January – May	-	-	-	-
	June – September	27	-	25	27
	October - December	-	-	-	-

2.3. Climate data

As the goal was to analyse the energy performance of the case studies described in Subsection 2.2, the EnergyPlus weather (EPW) file of each municipalities in Spain was generated. For this purpose, the software METEONORM was used. METEONORM is a software composed of 8,325 weather stations distributed around the planet and its use is supported by various studies [42–45]. Based on the data from these stations, the EPW of any location can be generated through a stochastic process [46]. To generate these EPW, the temperature period between 2001 and 2009 was chosen, as well as the radiation period between 1991 and 2010.

2.4. Cluster analyses

As it was possible to establish similarities between the energy demand obtained in the municipalities of Spain, cluster analyses were conducted, thus establishing groups of the existing energy inequalities in the country. The algorithm k-means was used for the cluster analyses. This algorithm is based on a sample X of n individuals which are classified into k groups, for which a partition W of that sample with $W = (w_1, \dots, w_a, \dots, w_b, \dots, w_k)$ is considered, so that $(\bigcup_{a=1}^{k} w_a = X, w_a \cap w_b = \emptyset, \mathrm{a} \neq \mathrm{b})$, fulfilling that the total sum of the sum of squares of Euclidean distances within each group is minimum:

$$\underset{W}{\operatorname{argmin}} \sum_{a=1}^{k} \sum_{x_i \in w_a} \sum_{r=1}^{p} (x_{ir} - \mu_{ar})^2 \tag{4}$$

At an operational level, the algorithm k-means includes the following stages: (i) the number of k groups used to conduct the analysis is identified; (ii) k individuals of the dataset are randomly chosen, constituting the initial centroids; (iii) by using the chosen association measurement, the distance of each individual to each k centroid is calculated; (iv) the k groups are created by allocating the closest centroid to each individual; (v) the new centroids of each existing k group are identified; (vi) steps 3 and 4 are repeated. This step could lead to two situations: either the step 5 begins if some of the individuals change the group in the step 4 or the cluster analysis process is finished when no individual changes the group in the step 4.

To select the number of groups optimally, 3 analyses were used. These analyses were based on the Elbow method, the silhouette index ($s(i)$), and the ratio between the sum of squares and the total sum of squares (BSS/TSS). The Elbow method consists in selecting the optimal number of k by minimizing the total within-cluster sum of squares (WSS) [47]. For this purpose, k-means is applied to different values of k and each WSS is calculated (see Eq. (5)). The route of the curve of WSS with respect to the number of k identified the elbow in the graphic, which is considered an indicator of the optimal number of groups. However, the elbow does not always find it clearly [47]. This characteristic takes place specially in cases in which there is a gradual and continuous change of data. In these cases, the method does not provide a unique possible solution, but a range of possible solutions which should be examined to determine the best solution. For this reason, this study combined the Elbow method with two indicators: $s(i)$ and BSS/TSS. The ratio BSS/TSS is a relation of the cluster compactness (see Eq. (6)). It is a percentage relation and can obtain values between 0 and 100%. The greater the value of the ratio, the greater the compactness of individuals within a group. As TSS=BSS+WSS, BSS is greater, so WSS will be lower.

$$WSS = \sum_{k=1}^{K} \sum_{i \in S_k} \sum_{j=1}^{p} \left(x_{ij} - \bar{x}_{kj}\right)^2 \tag{5}$$

$$\frac{BSS}{TSS} = \frac{\sum_{k=1}^{K} \sum_{j=1}^{p} \left(\bar{x}_{kj} - \bar{x}_G\right)^2}{\sum_{k=1}^{K} \sum_{j=1}^{p} \left(\bar{x}_{kj} - \bar{x}_G\right)^2 + \sum_{k=1}^{K} \sum_{i \in S_k} \sum_{j=1}^{p} \left(x_{ij} - \bar{x}_{kj}\right)^2} \tag{6}$$

Where $\mathrm{S_k}$ is the set of instances grouped in the k-th cluster, $\bar{x}_{kj}$ is the j-th variable of the cluster center for the k-th cluster, and $\bar{x}_G$ is the grand mean of the means of each cluster.

Finally, $s(i)$ is among the most used indexes in the cluster analysis [48]. The index shows the similarity of an individual with the other individuals within a same cluster. The quality of a cluster is therefore measured. For this purpose, the following equation is used:

$$s(i) = \frac{b(i) - a(i)}{max\{a(i), b(i)\}} \tag{7}$$

Where $a(i)$ is the mean distance between the individual (i) and the remaining points within a same cluster; and $b(i)$ is the minimum mean distance between the individual and the remaining clusters. The silhouette index can obtain values between -1 and 1. The meaning of these values determines the suitability of the cluster analysis: (i) if the value is between 0 and 1, then the observation is grouped correctly, obtaining optimal values those closer to 1; (ii) if the value is 0, then the individual is between two clusters, thus meaning that the individual shows very different characteristics from the remaining, so it cannot be group with them, or that the cluster analysis has excessively classified individual groups; and (iii) if the value is between -1 and 0, then the individual is placed in the incorrect group.

3. Results and discussion

3.1. Energy performance of buildings with the regulation before 2020.

First, the energy performance of the case studies was analysed with the limit values established in the CTE before the modification of 2020. The results showed the influence of the variations of the thermal properties of the regulation due to the climate zone in which the building is located, thus leading to inequalities in the energy performance of the same case study according to the municipality located. To make easier the understanding of this aspect, Figure 4 represents the spatial distribution of the values of heating and cooling energy demand in the 3 case studies in all the Spanish territory. Oscillations from the energy demand reached differences between 62.14 and 80.45 kWh/m^{2}year in heating, and between 12.15 and 24.72 kWh/m^{2}year in cooling. This aspect therefore showed that there were climate zones with characteristics favouring a greater energy demand. Based on the classification of WCS and SCS described in Subsection 2.1, the tendencies presented by the energy demand of the case studies can be seen according to the climate zone (see Figure 5). There was an ascending tendency in the energy demand as the winter and summer climate severity increased.

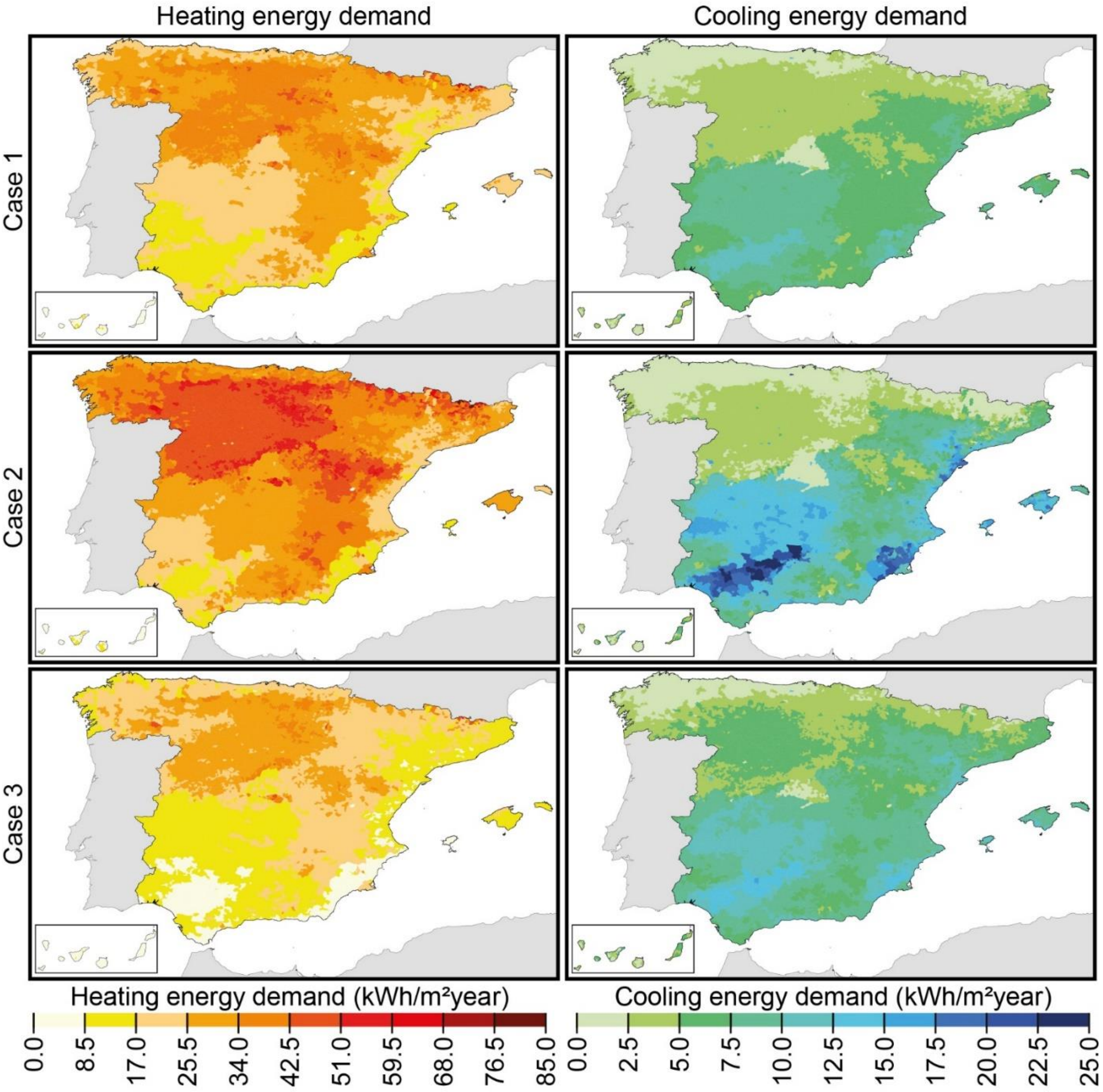

Figure 4. Distribution of the heating and cooling energy demand in the case studies by fulfilling the requirements included in the CTE before 2020.

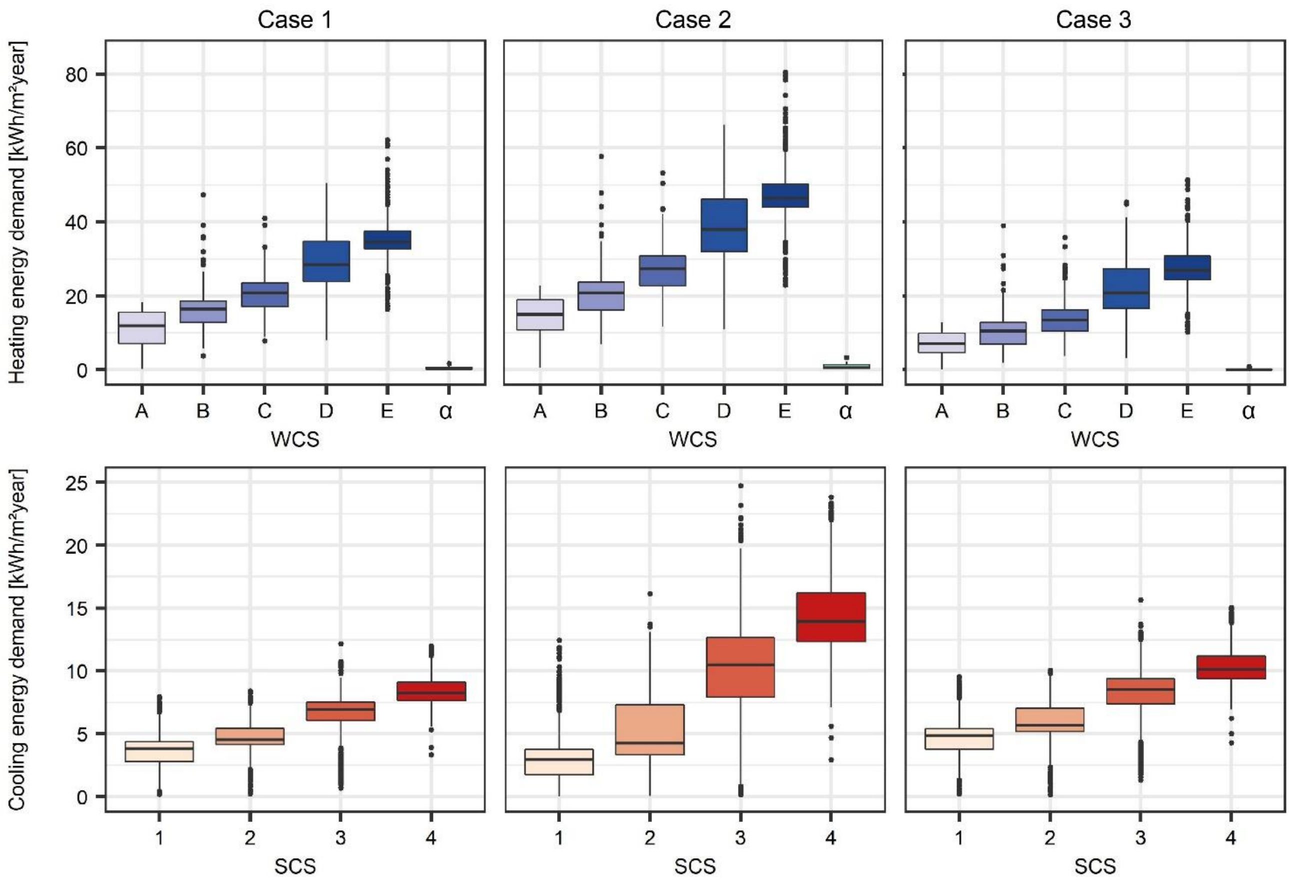

Figure 5. Box-plots with the distribution of heating and cooling energy demand according to the WCS and the SCS of the municipality (values obtained by fulfilling the requirements included in the CTE before 2020).

The ascending tendency in the values of quartiles was seen by analysing the case studies individually, paying special attention to Quartile 1 (Q1), or 25th percentile, and Quartile 3 (Q3), or 75th percentile. Regarding the heating energy demand, Q1 presented an ascending tendency oscillating between 4.44 and 9.37 kWh/m^{2}year, between 5.36 and 12.09 kWh/m^{2}year, and between 2.33 and 7.84 kWh/m^{2}year in the case studies 1, 2, and 3, respectively. Likewise, Q3 presented a similar tendency, with increases oscillating between 2.79 and 11.27 kWh/m^{2}year, between 3.11 and 16.44 kWh/m^{2}year, and between 2.84 and 11.04 kWh/m^{2}year in the case studies 1, 2, and 3, respectively. The zone E had the greatest values of energy demand, with a great concentration of the values of heating energy demand. Despite that the distribution of this zone presented some outliers (coinciding with mountainous zones, such as the municipalities located in the Pyrenees), the interquartile range was the lowest of the winter climate zones of the peninsula, with values between 4.78 and 6.24 kWh/m^{2}year. Also, the climate zone D presented the greatest interquartile range among all the existing climate zones, with values between 10.62 and 15.19 kWh/m^{2}year. This aspect could be based on the wide variety of municipalities in that climate zone, which reflected the possible climate variability of the municipalities of the region and the possibility of establishing a more detailed climate classification for the municipalities of that zone. Finally, the climate zone α was characterized by presenting a very low energy demand, with a low oscillation of the heating energy demand (the interquartile ranges in the case studies oscillated between 0.12 and 1.12 kWh/m^{2}year).

Regarding the cooling energy demand, there was a tendency similar to that of the heating energy demand. The increase of the summer climate severity therefore increased quartiles progressively. Q1 presented increases oscillating between 1.35 and 1.93 kWh/m^{2}year (case 1), between 1.60 and 4.60 kWh/m^{2}year (case 2), and between 1.41 and 2.18 kWh/m^{2}year (case 3), whereas Q3 presented a slightly greater increase: between 1.09 and 2.08 kWh/m^{2}year in case 1, between 3.53 and 5.37 kWh/m^{2}year in case 2, and between 1.61 and 2.36 kWh/m^{2}year in case 3.

These results among the distributions of the climate zones showed coincidences in the results of the energy demand obtained. In general terms, the coldest and warmest zones obtained the greatest values of energy demand, which could mean that the prescribed U-values are not appropriate. However, there were coincidences between the distributions of the severest zones with the less severe zones (e.g., climate zone E with climate zone A). This aspect showed that the cluster of energy inequalities which could take place in the country are not required to be adjusted to the climate classification established by the CTE. In this regard, the cluster analysis would obtain various groups of the municipalities according to the energy demand obtained, and the existing inequalities could be better verified. For this purpose, the cluster analysis was applied through k-means, as Subsection 2.4 describes. Unidimensional analyses were conducted of both heating and cooling energy demand in the 3 case studies: 4 and 5 groups were found according to the heating energy demand, and 3 groups according to the cooling energy demand (see Table 7). The values of $\frac{BSS}{TSS}$ and $s(i)$ guaranteed the independence of the groups generated. To make easier the understanding of the results obtained, Figures 6 and 7 show the distribution of the energy demand in the various clusters, as well as the winter and summer climate classification of the municipalities that fell within each group (the number order of clusters is based on the order of the groups generated by applying k-means). By analysing the results of heating energy demand, the centroid of groups found the existing energy inequalities: (i) in the case study 1, there were 5 groups whose centroids of heating energy demand were of 39.05, 34.07, 26.99, 20.65, and 12.99 kWh/m^2year for clusters 1, 2, 3, 4, and 5, respectively. This led to an energy inequality among the centroids of clusters with the greatest and the lowest energy demand of 26.06 kWh/m^2year (and with deviations which could be greater if the outliers of these clusters were considered); (ii) in the case study 2, there were 5 groups whose centroids of heating energy demand were of 52.05, 45.46, 35.97, 27.56, and 17.40 kWh/m^2year for clusters 1, 2, 3, 4, and 5, respectively. This led to an energy inequality among the centroids of clusters with the greatest and the lowest energy demand of 34.65 kWh/m^2year; and (iii) in the case study 3, there were 4 groups whose centroids of heating energy demand were of 30.71, 23.99, 16.17, and 8.96 kWh/m^2year for clusters 1, 2, 3, 4, and 5, respectively. This led to an energy inequality among the centroids of clusters with the greatest and the lowest energy demand of 21.75 kWh/m^2year.

Also, the clusters grouped municipalities from different climate zones. Clusters with a greater centroid grouped a larger number of municipalities with a higher winter climate severity. As the cluster had a centroid with a lower energy demand, zones of lower winter climate severity were grouped. However, all climate zones are included in all clusters, except the winter climate zones α and A. In clusters with a centroid with a greater heating energy demand, municipalities from the climate zones B and C were grouped, whereas in clusters with a lower heating energy demand, municipalities from the climate zone E were grouped.

Apart from the spatial analysis, it was also considered important to consider the population of each municipality and, therefore, the number of people that would fall into each cluster (Figure 8). With regard to the heating demand, clusters with larger demands are located in high mountainous areas and therefore underpopulated, and for such reason no more than 5.5% of the Spanish population lives in this cluster; on the contrary, clusters with a lower demand gather a large number of inhabitants. Cluster 4 includes 46.2%, 43% and 35% of The Spanish population for the case 1, 2 and 3, respectively. Looking at Figure 6, this means that roughly 40% of the Spanish population would live in dwellings whose energy demand for heating were between 7.20 and 10.16 kWh/m2year larger than cluster 5, the second more populated.

Regarding the cooling energy demand, there was a similar tendency. In the cluster analysis there were always three clusters grouping cooling energy demands, whose centroid values were as follows: in the case study 1, values of 7.51 kWh/m^2year were obtained for cluster 1, 4.54 kWh/m^2year for cluster 2, and 2.12 kWh/m^2year for cluster 3; in the case study 2, values of 14.72, 9.17, and 2.89 kWh/m^2year were obtained for clusters 1, 2, and 3, respectively; and (iii) in the case study 3, values of 9.28, 5.64 and 3.11 kWh/m^2year were obtained. Each cluster also grouped cities which belonged to the 4 summer climate zones, with the only exception of the climate zone 4 in cluster 3 from the case study 1. Nonetheless, this aspect showed again the possible limitations of the summer climate classification included in the CTE. In these cases, the population tendency varied according to the case study: case studies 1 and 3 presented the same population tendency (with a greater number of inhabitants in cluster 1), and the case study 2 presented a different tendency. The reason lied on a greater group of municipalities with a low number of inhabitants in the first cluster, similarly to the clusters of heating energy demand. High number were found in the various clusters obtained.

Table 7. Results of the cluster analysis of the values of heating and cooling energy demand (values obtained by fulfilling the requirements of the CTE before 2020).

Case study	Heating energy demand			Cooling energy demand		
	k	$\frac{BSS}{TSS}$	$s(i)$	k	$\frac{BSS}{TSS}$	$s(i)$
Case 1	5	92.7	0.54	3	84.1	0.60
Case 2	5	92.8	0.57	3	82.6	0.55
Case 3	4	90.2	0.57	3	87.2	0.63

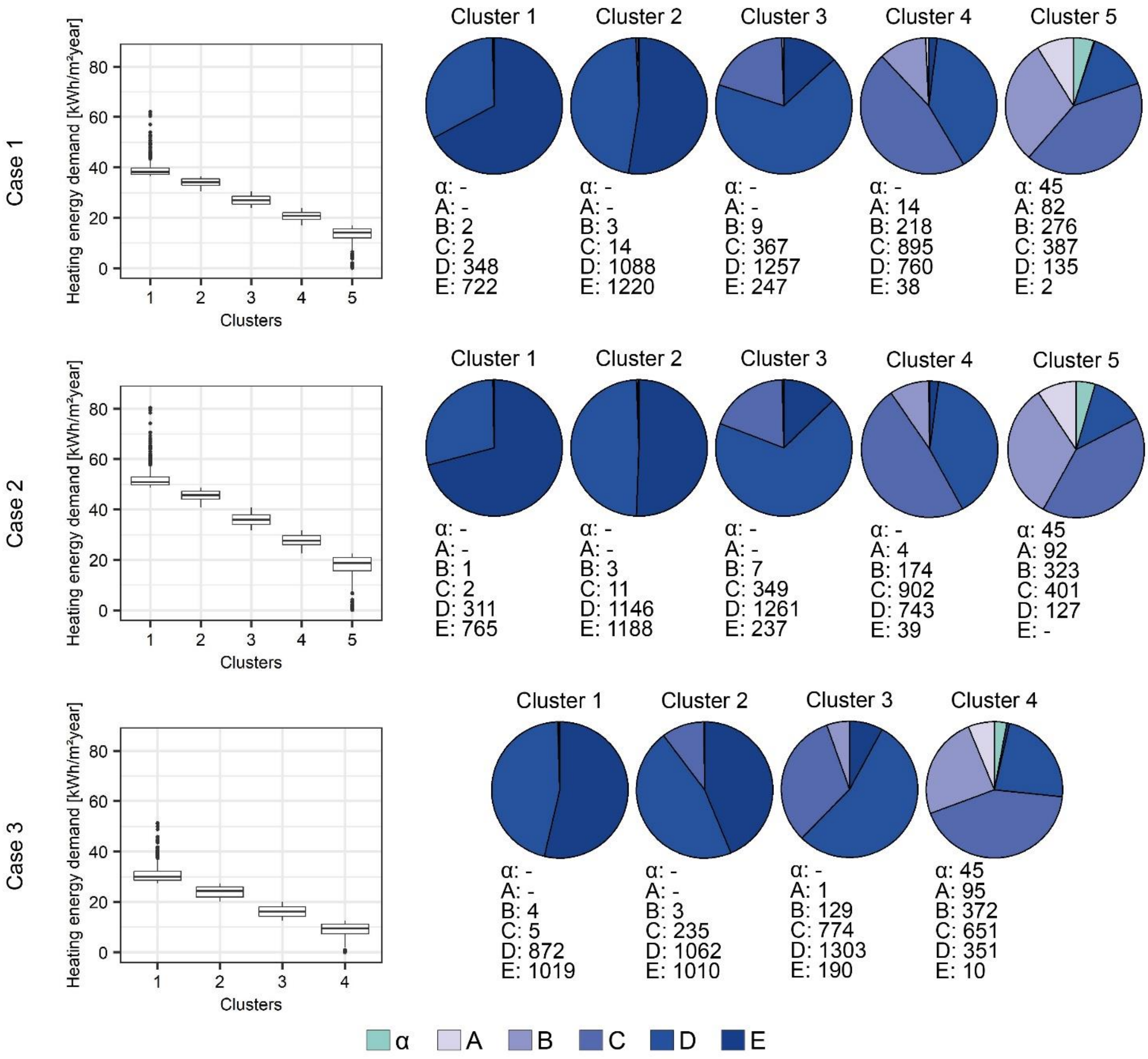

Figure 6. Distributions of the values of heating energy demand in each cluster, and WCS of the municipalities grouped in each cluster (values obtained by fulfilling the requirements included in the CTE before 2020).

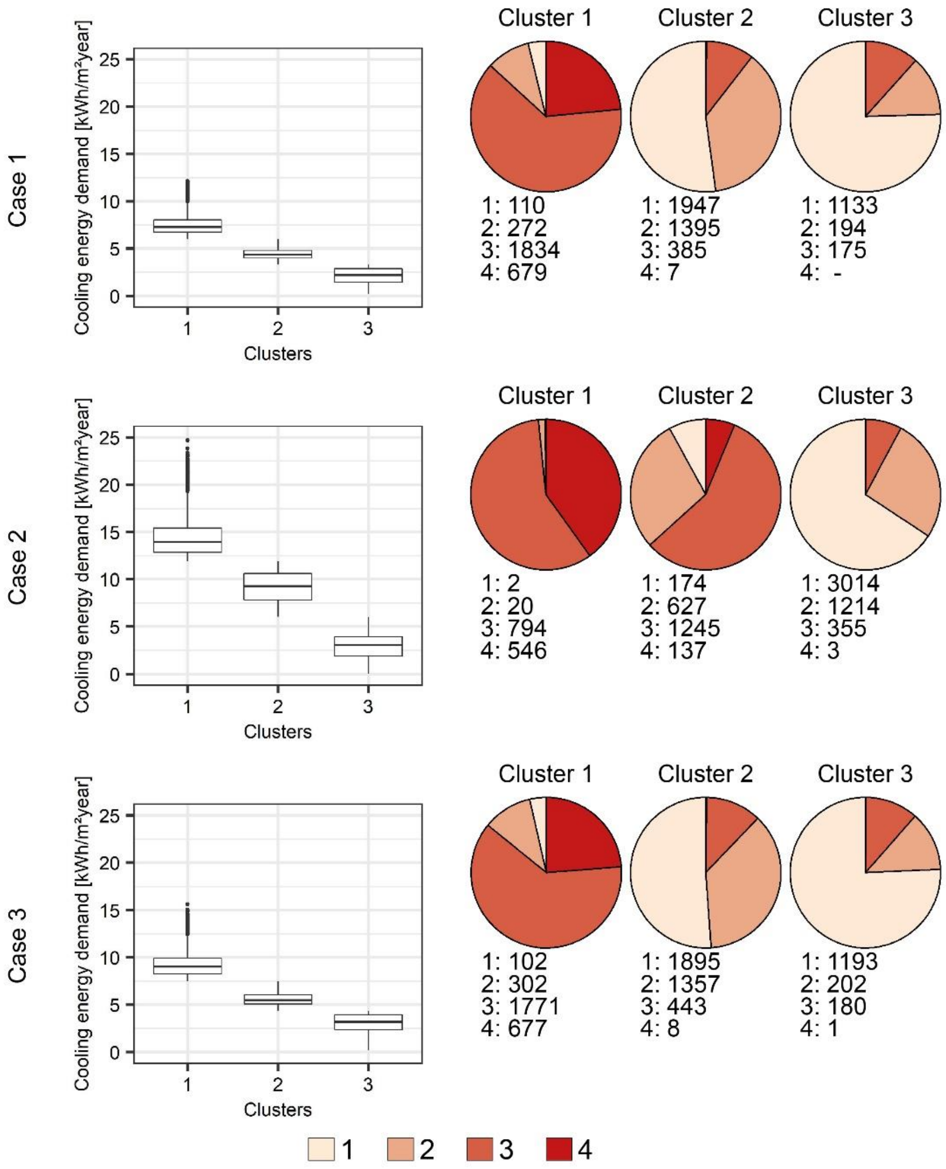

Figure 7. Distributions of the values of cooling energy demand in each cluster, and SCS of the municipalities grouped in each cluster (values obtained by fulfilling the requirements included in the CTE before 2020).

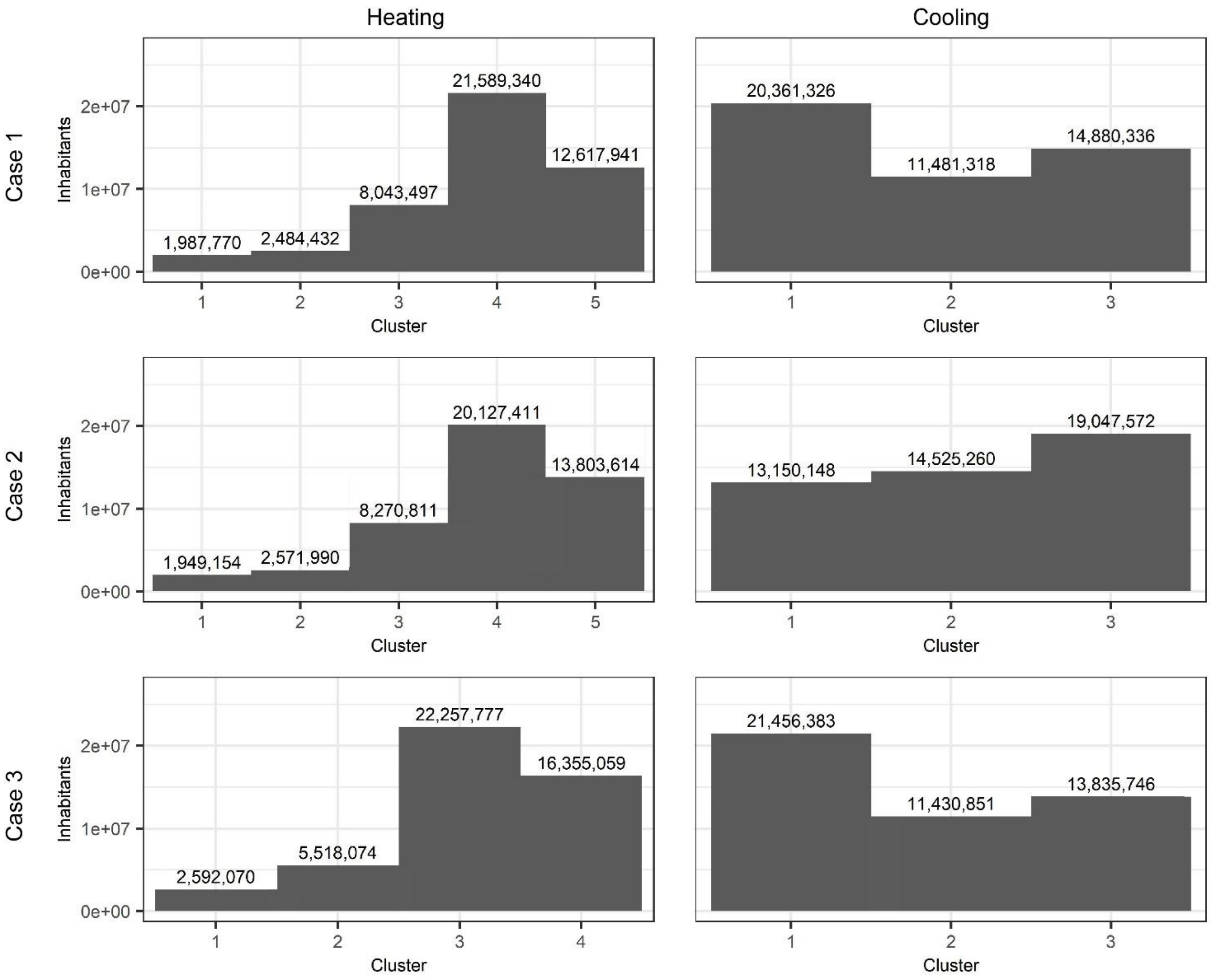

Figure 8. Distribution of the population of each cluster (clusters obtained for the energy demands of the case studies by fulfilling the requirements included in the CTE before 2020).

3.2. Energy performance of buildings with the regulatory update in 2020.

After analysing the energy performance of the case studies with the regulation before 2020 of the CTE, the situation of new or restored buildings adapted to the new thermal properties included in the modification of 2020 was assessed. Figure 9 represents the values of heating and cooling energy demand obtained in Spain. There were also energy inequalities among municipalities, although in this case the range of differences between the extreme values obtained was reduced: values in the heating energy demand oscillated between 36.59 and 69.52 kWh/m^{2}year, and in the cooling energy demand between 11.47 and 23.48 kWh/m^{2}year. Likewise, in winter and summer climate zones there was also the same ascending tendency in the values of energy demand as the climate severity increased (see Figure 10). Values of Q1 were therefore reduced with respect to those obtained with the designs of the CTE before 2020, oscillating between 3.62 and 7.45 kWh/m^{2}year, whereas in Q3 oscillated between 5.89 and 9.74 kWh/m^{2}year. This aspect showed the improvement of the new values of thermal transmittance adopted for the envelope elements according to the winter climate zone. In this regard, the heating energy demand was reduced with the new values of thermal transmittance (see Figure 11). An average reduction in the heating energy demand of 3.31, 5.99, and 6.82 kWh/m^{2}year was obtained in the case studies 1, 2, and 3, respectively. Regarding the cooling energy demand, the modifications of the thermal properties of the envelope had a lower effect on the improvement of the energy performance of the case studies, even the cooling energy demand slightly increased. This aspect was verified with the average values of reduction of the cooling energy demand: in the case study 1, there was a reduction of 0.09 kWh/m^{2}year, and in the case studies 2 and 3, there was an average increase between 0.03 and 0.16 kWh/m^{2}year. This aspect was also seen in the distributions of the summer climate zones included in Figure 10, as the values obtained with respect to those obtained with the old design criteria included in the CTE (i.e., before 2020) showed that the values of quartiles presented both increases and reductions: the values of Q1 presented variations oscillating from reductions of 0.19 kWh/m^{2}year to increases of 0.45 kWh/m^{2}year, whereas the values of Q3 presented variations oscillating from reductions of 0.33 to increases of 0.53 kWh/m^{2}year.

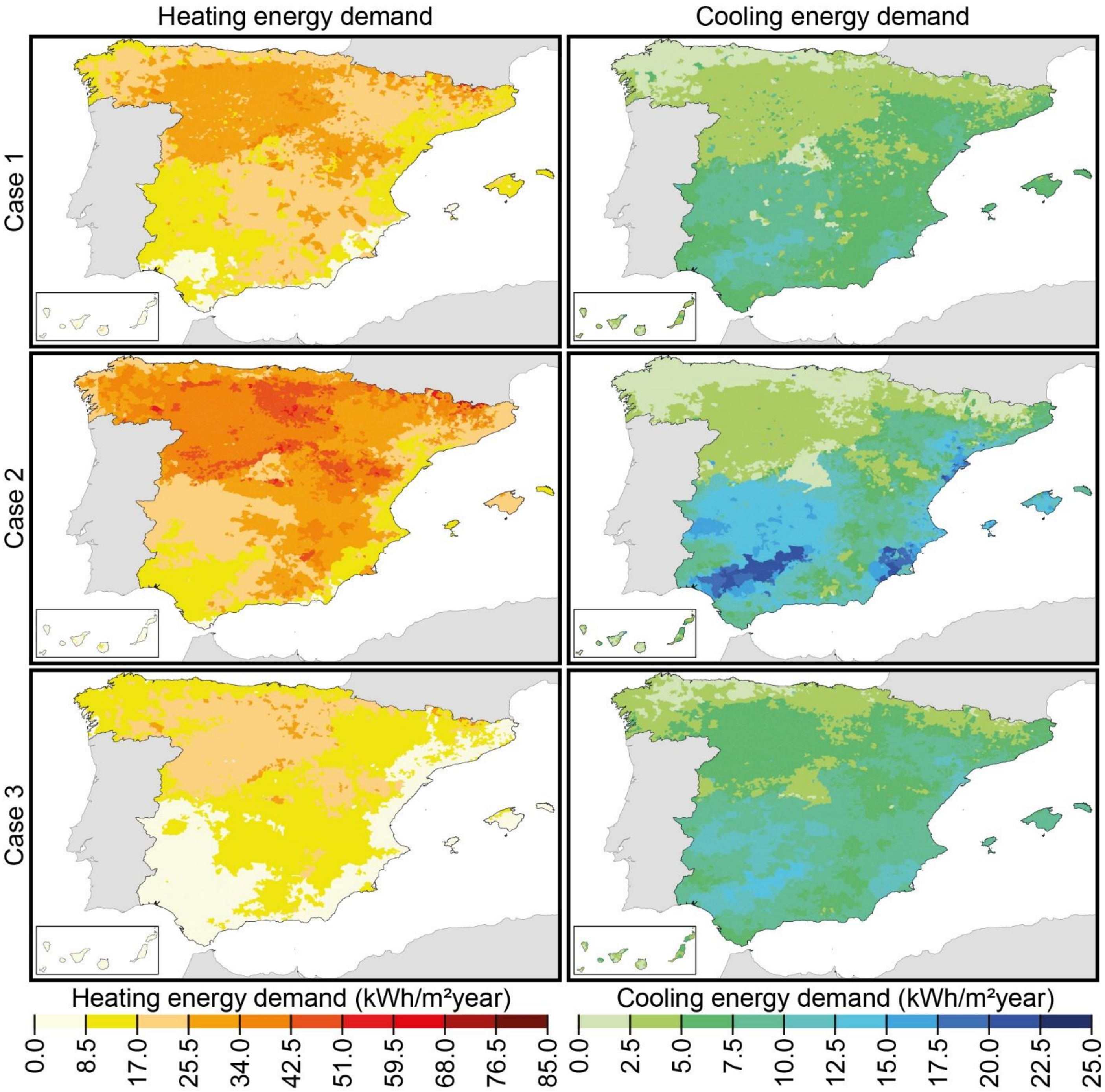

Figure 9. Distribution of the heating and cooling energy demand in the case studies by fulfilling the requirements included in the CTE after 2020.

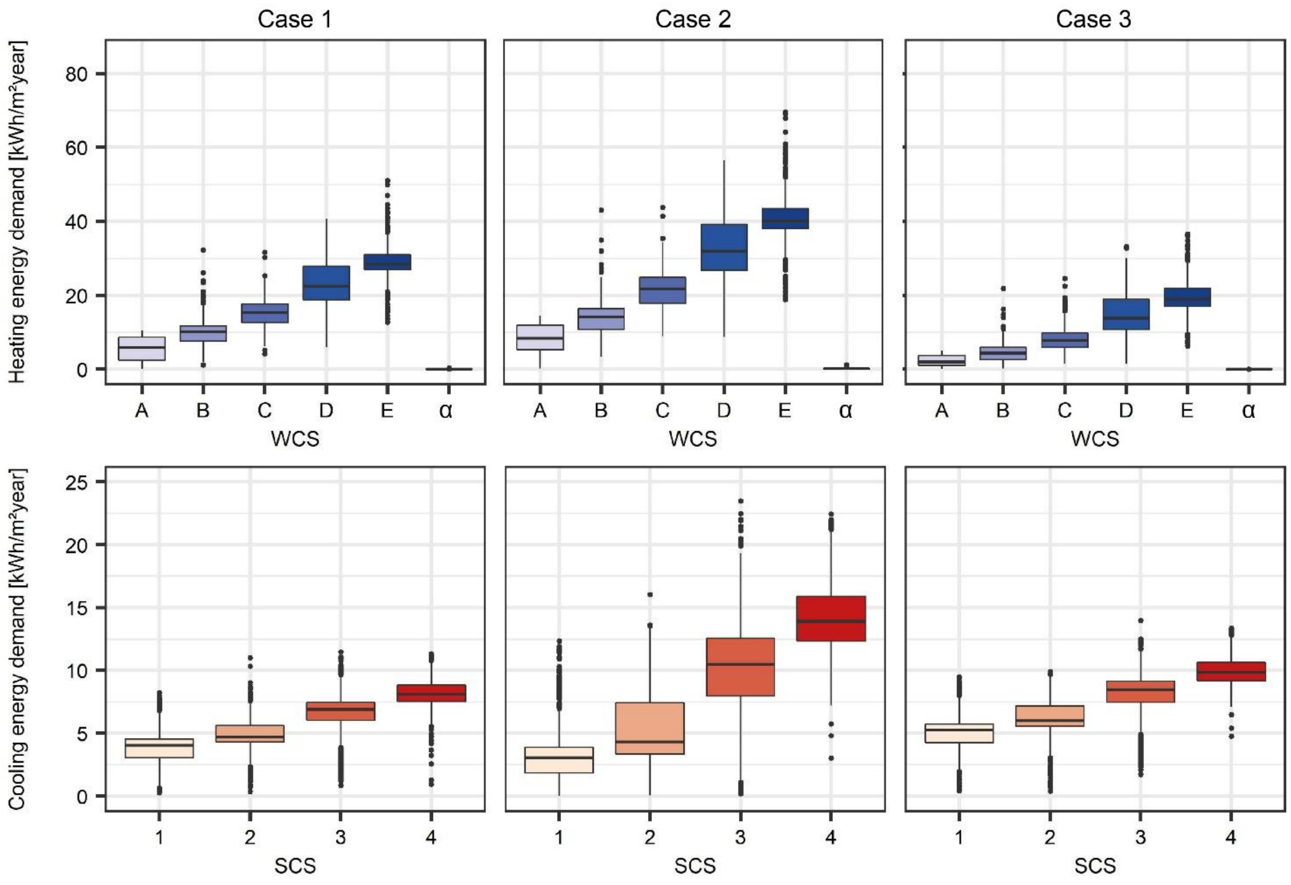

Figure 10. Box-plots with the distribution of heating and cooling energy demand according to the WCS and the SCS of the municipality (values obtained by fulfilling the requirements included in the CTE after 2020).

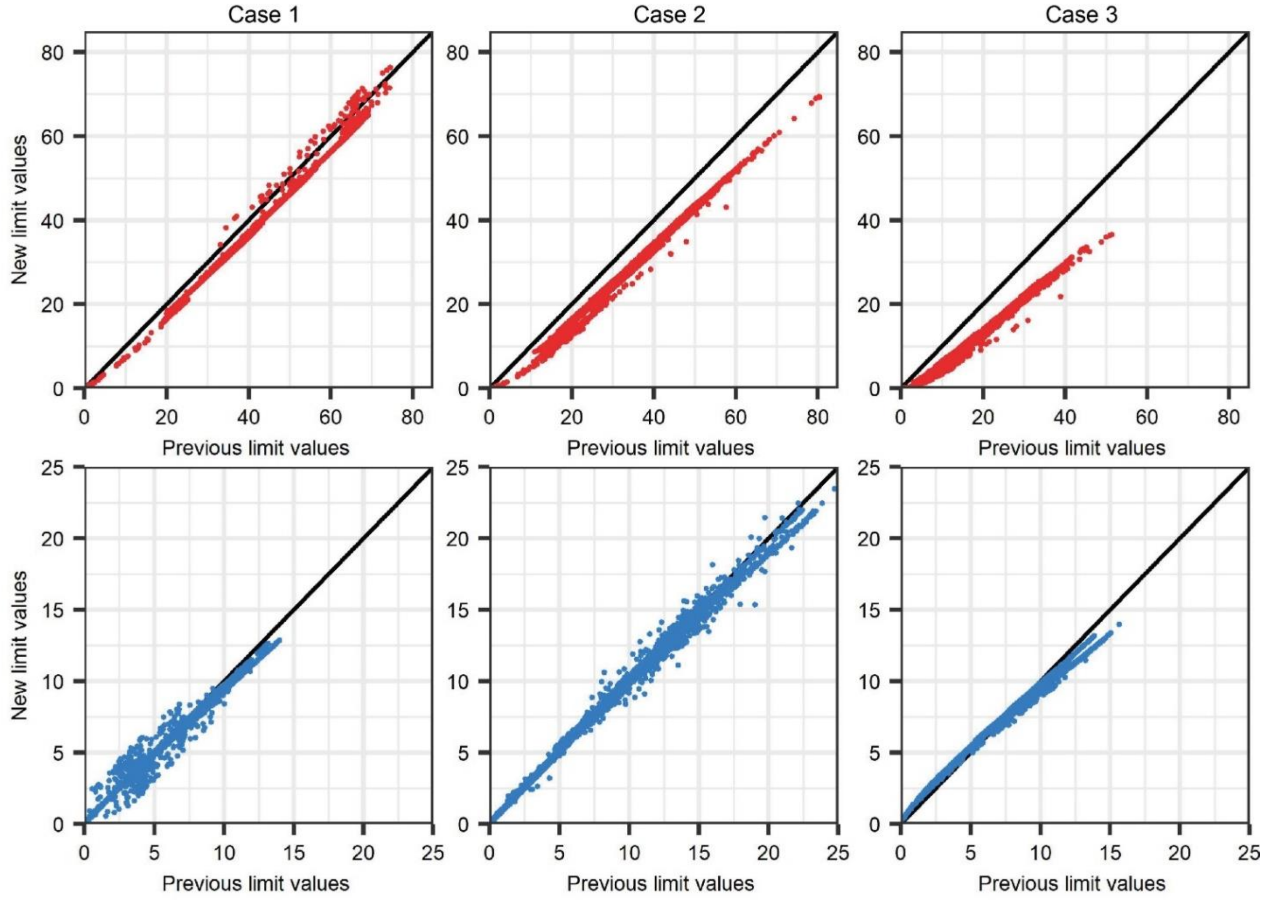

Figure 11. Dispersion diagrams between the values of heating (red) and cooling energy demand (blue) before and after the modification of the CTE in 2020.

Like the results of energy demand per climate zones obtained with the regulation before 2020, there were coincidences among the climate zones with the new limit values. So, unidimensional cluster analyses were again conducted for the heating and cooling energy demands of the 3 case studies (see Table 8). The optimal number of clusters was very similar to that of the results before 2020, with the only exception of the case study 1, which reduced the number of groups from 5 to 4. There were also reductions in the values of centroids. As for the groups of heating demand, centroids were reduced between 3.34 and 7.24 kWh/m^{2}year (see Figure 12), and in the cooling demand, the reductions oscillated between 0.08 and 0.54 kWh/m^{2}year (see Figure 13). Likewise, it was possible to verify how this modification generated a greater group of municipalities in clusters with the lowest heating energy demand (see Figures 12 and 13). In this regard, the number of municipalities increased between 11.33 and 46.25% in the groups with the lowest heating energy demand, thus varying the number of inhabitants of the clusters (see Figure 14). Also, the number of inhabitants increased between 15% and 56% in the clusters with the lowest heating energy demand. However, the cooling energy demand increased the number of inhabitants in the most unfavourable groups because of the low effectiveness of the new CTE limit values (these values are not useful to lessen the cooling energy demand). The same occurred in the number of municipalities in the clusters of cooling energy demand because the number of municipalities was increased between 1.24 and 13% in the groups with the highest energy demand. Although the improvement of thermal properties could guarantee buildings with a better energy performance for a greater number of inhabitants, the energy inequalities kept showing the limitations presented by the regulation of the CTE in Spain as regards the regulation of the thermal properties of the envelope. Likewise, the modifications of the limit values of the envelope hardly increased the energy performance of buildings in warm periods.

Table 8. Results of the cluster analysis of the values of heating and cooling energy demand (values obtained by fulfilling the requirements of the CTE after 2020).

Case study	Heating energy demand			Cooling energy demand		
	k	$\frac{BSS}{TSS}$	$s(i)$	k	$\frac{BSS}{TSS}$	$s(i)$
Case 1	4	90.6	0.58	3	84.5	0.61
Case 2	5	93.1	0.57	3	83.6	0.57
Case 3	4	90.8	0.58	3	87.6	0.63

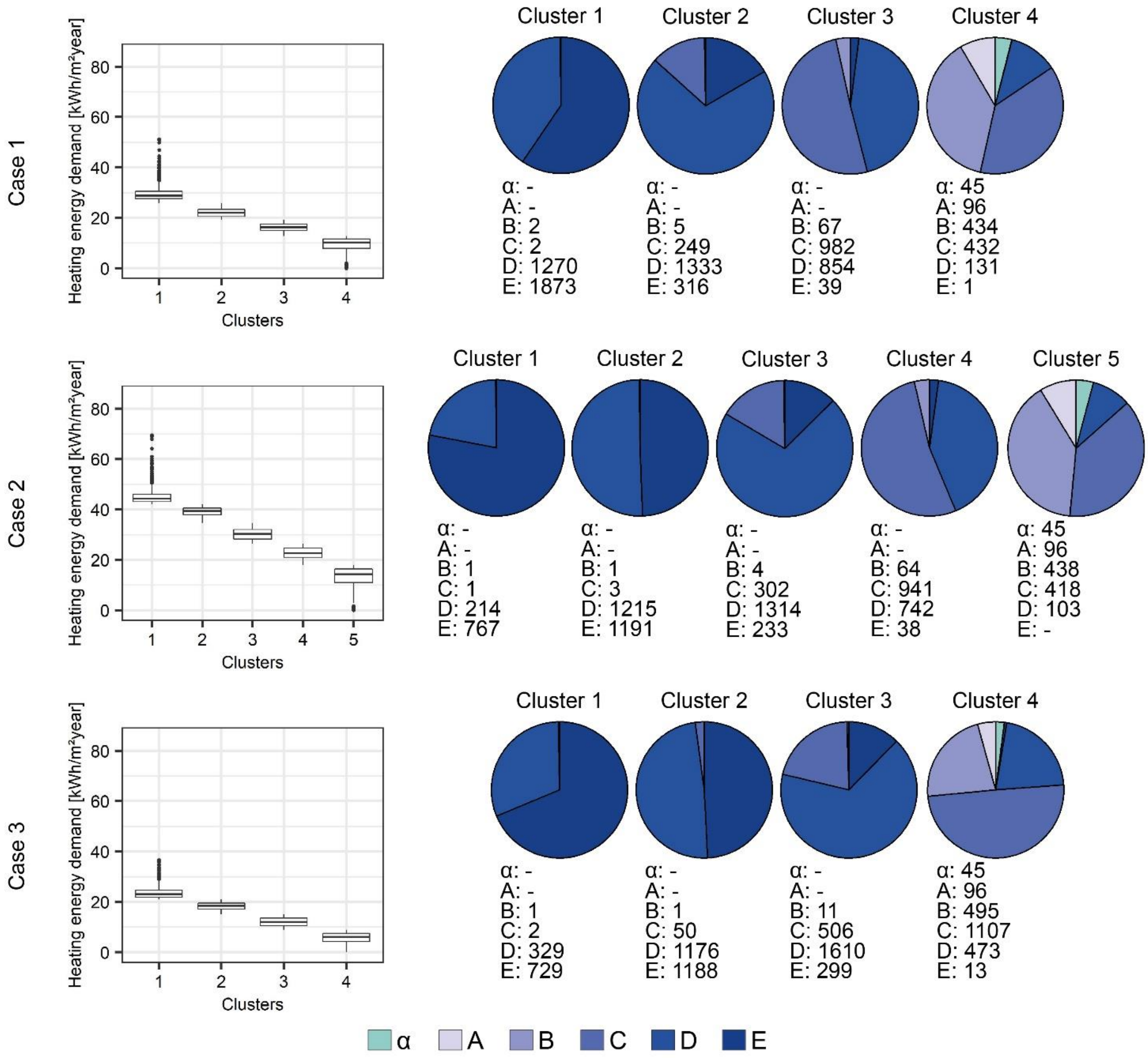

Figure 12. Distributions of the values of heating energy demand in each cluster, and WCS of the municipalities grouped in each cluster (values obtained by fulfilling the requirements included in the CTE after 2020).

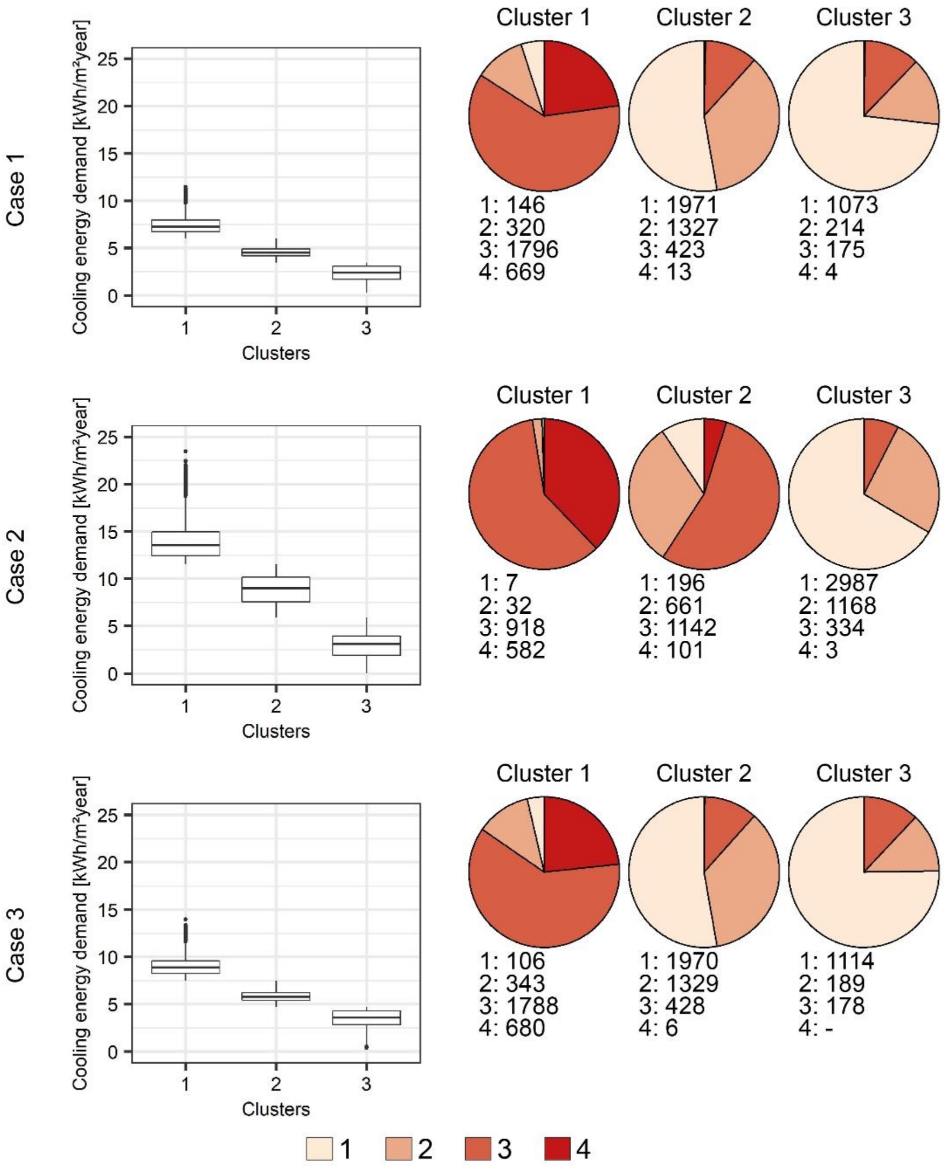

Figure 13. Distributions of the values of cooling energy demand in each cluster, and SCS of the municipalities grouped in each cluster (values obtained by fulfilling the requirements included in the CTE after 2020).

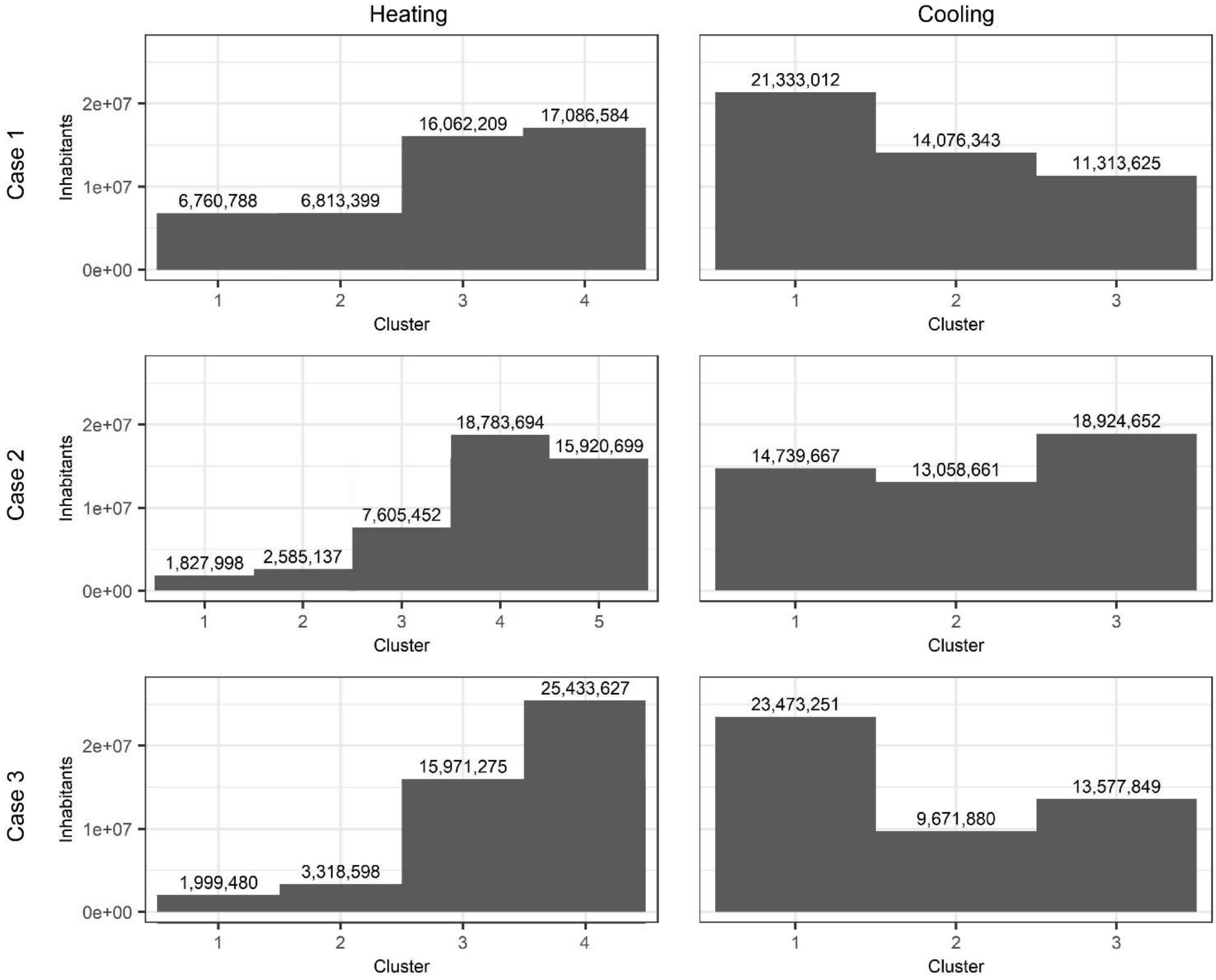

Figure 14. Distribution of the population of each cluster (clusters obtained for the energy demands of the case studies by fulfilling the requirements included in the CTE after 2020).

4. Conclusions

This study aimed at clarifying whether the current Spanish standard on energy efficiency in building may suit the implementation of the recent nZEB standard; by means of extensive computer simulations of each municipality in Spain, energy inequalities within the same climate zone were analyzed and new clusters were proposed to better reflect the real heating and cooling demand of common housing prototypes.

The main results of the study indicated that the current climate zones in the Spanish building code should be reconsidered in the near future. The current standard assumes that the greater the winter and/or summer climate severity, the more insulated the building should be, which would result in a lower energy demand for heating and/or cooling; it also assumes that the higher the altitude, the colder the climate. This study has shown that this system does not prevent buildings from using larger amounts of energy. Even though the current standard sets stricter limits for the U-value of the external envelope depending on the WCS, dwelling located in the coldest zones (E) demand, as an average, between 350%-300% more energy than those located in the warmer zone (A). Since the standard does not envisage limits for the cooling season, no clear tendency could be expected for this matter; this study also clarified that more insulated buildings do not necessarily have lower cooling demands: In this case the oscillations between the coldest zone (1) and the warmest (4) zone were between 175% and 400%, which can be explained by the different shape and compactness of the 3 considered typologies. Additionally, the same building located in different municipalities that fall in the same climate zone also show substantial variations, which can be as large as 10 kWh/m^{2}year in the heating demand for buildings in zone D, and 4.5 kWh/m^{2}year in the cooling demand if located in zone 3.

The same tendency was observed when the analysis was conducted using the newly proposed U-limits that comply with the nZEB standard. Despite the numbers are a bit different, it was also concluded that dwellings in the coldest and warmest zones would demand more energy for heating and cooling. Again, disparities in the form of a wide interquartile range were observed for the same building located in different municipalities belonging to zones D (around 13 kWh/m^{2}year) and 3 (around 4.5 kWh/m^{2}year). However, this research also clarified that this new benchmark could reduce the average demand for both cooling and heating.

Since it was proven that this climate classification could not accurately represent the energy demand for heating and cooling, this study also proposed a new climate classification with the aim of reducing energy inequalities, and it was also applied to both scenarios: current standard and nZEB benchmark. With regard to the first scenario, 5 clusters were identified for heating and 3 for cooling, and it can be concluded that they better represent the energy demand: The interquartile ranges are much smaller, below 2.5 kWh/m^{2}year for all cases, except for cluster 5 of heating demand; this can be explained because they group municipalities from 5 and 6 different climate zones; outliers are also fewer in comparison. The same tendency can be observed after the implementation of the nZEB standard, with compact clusters that show smaller variations for both heating and cooling demand.

This study also has some methodological implications. The current climate classification, in the forms of WSC and SCS, is based on a simplified model that assumes that energy demand for heating and cooling depends on the temperature gap between the inside and the outside, calculated on a daily basis, and in the case of the heating demand, on the amount of solar radiation that may allow for passive heating. This approach is basically the same as in the first Spanish regulation from 1.979, and this study has shown, by means of extensive simulations, that this standard might not necessarily lead to lower energy demands. Conversely, the flourish of computer simulation software can allow for extensive simulations of different typologies on an hourly basis, considering also different schedules of use and internal heat gains. The authors consider that the present research paves the way for a new methodological approach towards more effective regulations on building energy efficiency, which would require a robust and structured approach that considers representative typologies of buildings; this study draws conclusions on 3 representative typologies of residential buildings, but this calls for future research considering multiple combinations of schedules of uses, U-values and internal heat gains, as well as the simulation of other parameters of the external envelope, such as the periodic thermal transmittance.

In conclusion, in a time when the building industry is undergoing significant regulatory changes towards the nZEB standards, and also facing the pressing issue of energy efficiency and climate change, this study can be of use to Spanish designers, stakeholders and lawmakers in two ways: Rethink the current climate classification to reduce the energy inequalities and shape a new methodological approach, based on detailed simulations, that allow for a more reliable forecasting of the heating and cooling demand of buildings.

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