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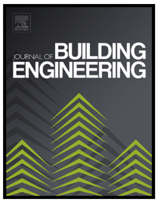

Climate classification for new and restored buildings in Andalusia: Analysing the current regulation and a new approach based on k-means

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ABSTRACT

The Spanish Building Technical Code (CTE) sets that all new and restored buildings meeting its requirements have nearly zero energy consumption. This code is based on establishing limit values according to the climate zone. However, previous studies have shown both the existence of energy inequalities among regions and the limitations related to the direct application of these criteria. This work analyses the climate classification included in the CTE and presents a new climate classification methodology based on k-means. For this purpose, the region of Andalusia was chosen, and 8 case studies located in the 779 cities of the region were analysed. The analysis was performed in both the current scenario and future scenarios throughout the 21st century. The results showed the limitations related to the climate classification included in the CTE, greatly coinciding among the various zones and with high interquartile ranges in the energy demand distributions of each zone. By using the climate classification obtained with k-means, the new zones are independent of each other, with low interquartile ranges.

1. Introduction

The reduction of environment degradation is included in current societies' sustainable goals. Through various international policies and agreements, such as the Kyoto Protocol or the Paris Agreement [1], countries all over the world have established goals as regards sustainability and the reduction of greenhouse gas emissions because aspects such as climate change could affect future generations. The Intergovernmental Panel on Climate Change (IPCC) has presented in various reports [2,3] the expected climate change tendencies throughout the 21st century and their consequences for habitability: temperature and sea level rise, ocean acidification, extinction of species, and the emergence of pandemics. These aspects have already taken place due to the strong tendency of the extinction of species [4] or the COVID-19 pandemic [5,6]. This situation arises from the greenhouse gases (GHG) emitted by various anthropogenic activities, including the use of buildings [7]. The high building energy consumption because of a deficient building stock [8–12] is causing a building environmental impact. By way of example, the building stock in Europe was responsible for 49% of the total energy consumption [13,14] and 36% of the GHG emissions [15,16]. According to the international agreements, the European Union has therefore set the goal of reducing GHG emissions progressively until 2050, thus achieving a low-carbon economy [17]. For this purpose, GHG emissions should be reduced in various sectors, including building, with the aim of reducing these emissions by 90% [17].

Moreover, establishing appropriate measures is crucial to energy renovate the existing buildings [18–21]. With these renovations, the existing building stock would achieve the category of nearly zero energy consumption buildings (nZEB). The most appropriate energy conservation measures have been widely studied according to the characteristics of the building, its location, users, and installations. In this regard, most studies are also related to the influence of the envelope on the building energy performance as their surface is large, with a great heat transfer. Aksoy and Inalli [22] assessed the reduction of heating energy demand obtained by improving the thermal transmittance in buildings located in cold regions. Reductions by almost 30% were obtained. Similarly, Yuan et al. [23] analysed the influence of the location of the insulating material, so being placed in the exterior reduced energy consumption more than 18% in comparison with being placed in the interior. Likewise, the use of innovative materials in the envelope, such as phase

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change materials [24] or aerogels [25], could improve the building energy performance in comparison with traditional materials [26], although the price and the payback period are high [27]. Moreover, other envelope elements (e.g., thermal bridges) could greatly affect energy consumption. Ramalho de Freitas and Grala da Cunha [28], Ge et al. [29], and Bienvenido-Huertas [30] have reported that the variation of the linear thermal transmittance could save energy consumption by 20%. Regarding the improvements in installations, research works have been focused on self-consumption and user impact. Catrini et al. [31] analysed the use of self-consumption in commercial buildings located in the north of Italy. The results showed that the use of cogeneration systems improve the energy efficiency and sustainability of these buildings, apart from having a low amortization period because of selling the surplus energy. Likewise, users' behaviour could strongly affect energy performance. Wan et al. [32] and Spyropoulos and Balaras [33] showed that varying setpoint temperatures up to 4 °C could significantly save energy consumption. Hamburg et al. [34] studied the influence of users' behaviour on the actual energy performance of buildings designed for nZEB. The results showed that users' behaviour could increase the energy consumption of nZEB by 29%. In addition, the need for considering energy losses in the distributions of the installations was reported because it significantly contributes to nZEB energy consumption.

Thus, the most acceptable measures for energy restoration works have been shown. However, a state regulation as regards building energy efficiency is crucial to accurately know the characteristics that buildings should have, thus guaranteeing an appropriate energy restoration of the existing buildings. In Spain, the Spanish Building Technical Code (CTE) [35] establishes the requirements that buildings should meet, including various aspects such as energy efficiency [36]. The fulfilment of the characteristics related to energy efficiency which are included in the CTE guarantees that the restored building is nZEB, regardless of the limitations reported by some studies, e.g., Attia et al. [37], to achieve nZEB in the climates of the Mediterranean region. Regarding the criterion to establish the limitations or characteristics that buildings should fulfil, the CTE defines limit values according to the climate zone of the building. This approach is like the regulation from other countries [38]. However, climate classification approaches could present limitations to achieve low building energy consumption. In this regard, studies conducted in other countries, such as Chile, have stressed both the possible limitations of the climate zones included in the regulation [39] and the variations obtained by various classification methodologies [40], thus emerging energy inequalities among the climate zones by fulfilling the same energy efficiency regulation. Bienvenido-Huertas et al. [38] showed that fulfilling the energy efficiency regulation of several countries, including Spain, oscillated the building energy demand, and a similar behaviour could not be guaranteed in each country. Recently, Bienvenido-Huertas et al. [41] analysed the limitations related to the CTE to fulfil the nZEB category in all the cities in Spain. The results showed that the energy demand of various regions in the country significantly varied and that the climate classification of the country should be reviewed to guarantee a most effective control of building energy demand. In this regard, characteristics more adapted to each region could be established, thus reducing the risk of energy poverty in certain regions [42,43] and guaranteeing that decarbonisation goals are easier achieved in the sector.

This study analysed the design of a new criterion of climate classification in Spain based on the cluster analysis. Cluster analyses are a methodology to group individuals which have presented good results in other similarity approaches among variables at a geographic level [44–46]. For this reason, some studies, such as Xiong et al. [47] in China, applied cluster analyses to establish climate zones. Andalusia, one of the Spanish regions with both the most deficient building stock and a great variety of climate zones, was chosen as the study zone [21,41]. This study was also aimed to considering the possible implications and modifications taking place because of climate change. In this regard, climate change could change future building energy demands due to the variation of the severity of seasons [48–50], thus implying that the climate classification designed by the CTE could be less adapted in the future. Some studies conducted in other countries, such as Chile, have reported the possible limitations of the climate zone included in the regulation [51]. This study did not just analyse the performance and effectiveness of the classification approaches of both the CTE and the cluster analysis in the current scenario, but also assessed the tendencies and changes expected throughout the 21st century because of climate change.

2. Methodology

2.1. Study zone

This study analysed the 779 towns of Andalusia. This region is in the south of Spain (Fig. 1) and is characterized as the most populated region in the country. The most recent population data recorded by the Spanish Statistical Institute [52,53] indicate that the population in this region is greater than 8 million inhabitants, with this number of inhabitants being greater by 9.62% in comparison with the second region with the greatest number of inhabitants. However, the economic data of the region are not positive. The values of aspects such as the employment rate and household annual incomes are the lowest in the country [54], thus contributing to the emergence of fuel poverty cases in the region [55]. Regarding the characteristics of the building stock, 50.14% of the existing buildings in the region was built before the first Spanish regulation on building energy efficiency [9]. Consequently, more than half of buildings were built with low effective design criteria which, together with the envelope ageing, implies very deficient energy performance [21]. Thus, most buildings existing in the region should be restored and energy adopted [35].

2.2. Approaches of the climate zones analysed

The regulation on building energy efficiency in Spain is today included in the CTE [38,41]. This regulation establishes various limit values related to building energy performance, such as envelope thermal properties or primary energy consumption. Various limit values are established for each according to the climate zone of the building. The climate zone is determined by the climate classification in Spain carried out by the CTE. The classification is based by dividing the country into two types of zones according to the seasons: a classification for the winter months (i.e., the months when heating systems are used) and another for the summer months (i.e., the months when cooling systems are used). This classification was determined according to the climate severity (mainly determined through the degree-days with a base temperature of 20 °C) and is referenced to the climate in Madrid. On the one hand, winter climate zones are divided into 5 using letters: A, B, C,

Fig. 1. Location of the autonomous region of Andalusia.

D, and E. The zone A corresponds to the zone with the least winter severity (i.e., the least heating energy demand), and the zone E corresponds to the zone with the greatest severity (i.e., the greatest heating energy demand). The CTE establishes 4 types of summer climate zones using a number: 1, 2, 3, and 4. Following the same criterion as with the winter climate zones, the zone 1 corresponds to the least severe zone, and severity increases until zone 4, which corresponds to the zone with the greatest cooling demand.

Using these zones is crucial to regulate the establishments of limit values. In this regard, the limit values established for the envelope thermal transmittance are organized according to the winter climate zone [56]. This is based on supposing that the energy demand of a building located in a certain climate zone is the same in all the cities in that zone (i.e., a building in Seville (zone B4) should have an equal or similar energy demand if it is in Cordoba (B4)). Therefore, the same building located in distant cities in the territory would have the same energy consumption if they were in the same climate zone. This criterion based on classifications with degree days is common in other countries [38]. In addition, some studies have tried to apply the CTE climate classification system in other countries, such as Chile [51]. However, several studies have shown the possible limitations related to this aspect, contributing to the emergence of energy inequalities among cities whose new or restored buildings fulfil the characteristics established by the regulation [38,40].

For this reason, this study designed a new climate zone. Cluster analyses were performed using k-means as a grouping algorithm [57]. This algorithm was used by the many studies based on cluster analysis and focused on the energy analysis of buildings. The reason is its ease of implementation and the viability of the groups obtained [58]. Thus, the algorithm has been used by several studies related to the topic of this research work: (i) Gao and Malkawi [59] used k-means for the comparative evaluation of the energy performance of buildings in the USA; (ii) Arambula Lara et al. [60] used k-means to detect clusters in the energy performance of school buildings in Italy; (iii) a similar study was carried out by Gaitani et al. [61], in which k-means allowed school buildings in Greece to be grouped according to their heating demand; (iv) Fazlohalli et al. [62] applied k-means to make clusters of urban areas to optimize energy designs, and (v) Zhan et al. [63] used k-means to determine similarities in buildings through their operational similarities, thus facilitating energy assessment.
k-means starts with a sample X of n cases divided into k groups, for which a partition W of that sample is considered with $W = \left(w_1, \dots, w_a, \dots, w_b, \dots, w_k\right)$, so $\left(\cap_{a=1}^{k} w_a = X, w_a \cap w_b = \emptyset, \mathrm{a} \neq \mathrm{b}\right)$, thus fulfilling that the total sum of the sums of squares of the Euclidean distance within each group is minimum (Eq. (1)). As for its operation, 6 stages are distinguished with k-means:

1. The number of k groups used for the analysis is identified.
2. The k individuals of the dataset (i.e., the initial centroids) are randomly selected.
3. The distance of each individual to each k centroids is calculated.
4. The k groups are formed by assigning each individual to the closest centroid.
5. The new centroids of each existing k group are identified.
6. Stages 3 and 4 are repeated. This stage could result in two situations: (i) next comes stage 5 if an individual changes the group in stage 4, repeating the cycle; and (ii) the cluster analysis process ends when no individual changes the group in stage 4.

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

The cluster analysis was performed to establish independent climate classifications for winter and summer. Two climate zones were therefore established for each scenario. The number of groups of each zone was the same as that used by the CTE for its zones: 5 for winter, and 4 for summer (i.e., the cluster analysis was performed with a k-value of 5 for the winter period, and with a k-value of 4 for the summer period). The goal was to compare representatively the various climate zones analysed in the research. Climate classifications were established with the cluster analysis in both current and future scenario. In the latter there were independent climate classifications for the years 2050 and 2100. For this purpose, data from an energy simulation process described in Subsection 2.3 were used. Energy demand data from several case studies were used for each cluster analysis as input variables, so each input variable corresponded to a case study. Various heating and cooling classifications were established according to the type of input variable used: heating energy demand was used for heating classifications, and cooling energy demand for cooling classifications.

To assess the quality of the classifications, the Silhouette index was assessed [64]. The Silhouette index allows the similarity of an individual to be verified with the other individuals in a same group and is a quality indicator of a group. For this purpose, the average distance between an individual and the other points in the same group is determined ($a\left(i\right)$), as well as the minimum average distance between the individual and the other groups ($b\left(i\right)$) (Eq. (2)). The silhouette index can have values between −1 and 1. This value indicates the quality of grouping the individuals: (i) if the value is between −1 and 0, the individual is in the wrong group; (ii) if the value is 0, the individual is between two groups. This could mean that either the individual shows very different characteristics from the rest that do not allow them to be grouped with the others or that the cluster analysis has carried out an excessive classification of the individual groups; and (iii) if the value is between 0 and 1, the individual is correctly grouped, and those closer to 1 obtain optimal values.

$$s\left(i\right) = \frac{b\left(i\right) - a\left(i\right)}{max\left\{a\left(i\right), b\left(i\right)\right\}} \tag{2}$$

2.3. Case studies and climate data

To know the limitations of the climate zones, an energy simulation process was conducted in 8 case studies (Fig. 2). These case studies were also useful to perform the cluster analyses as heating and cooling energy demand data were used as input variables. The case studies have different characteristics related to geometry, surface, and glazed surface percentage, so various possibilities of the building stock were analysed. Thus, the case studies correspond to the most common types of construction in the building stock in Spain [65]. In this regard, various studies have shown that the most common types of construction in Spain have floors with the form of H, U, or without courtyards [9,66,67]. These types are common in both new and existing buildings; therefore, these case studies correspond to both new constructions and energy renovations. The case studies were modelled and simulated with EnergyPlus. Moreover, the envelope thermal properties used in all case studies were the same. For this purpose, the most effective limit values established by the CTE before being updated were used: 0.55 W/m^{2}K for the façade, 0.35 W/m^{2}K for roofs, and 2.50 m^{2}K for windows. These values were defined in the envelope element of the models. The load profile used was that defined by the CTE for residential use (see Table 1). The use of this profile allowed both the loads inside the building and the setpoint temperatures to be defined, so the heating and cooling energy demands were calculated [68]. This load profile is characterized by the occupancy variation according to the day: from Monday to Friday, the occupancy load varies between 0.54 and 2.15 W/m^2 (sensible load) and between 0.34 and 1.36 W/m^2 (latent load). The load of lighting devices and equipment has the same use profile, which varies between 0.44 and 4.40 W/m^2 according to the hour of the day. Regarding the setpoint temperatures, the profile for residential buildings defined in the CTE was also used (see Table 2). These setpoint temperatures are based on a static thermal comfort model in which users' thermal expec-

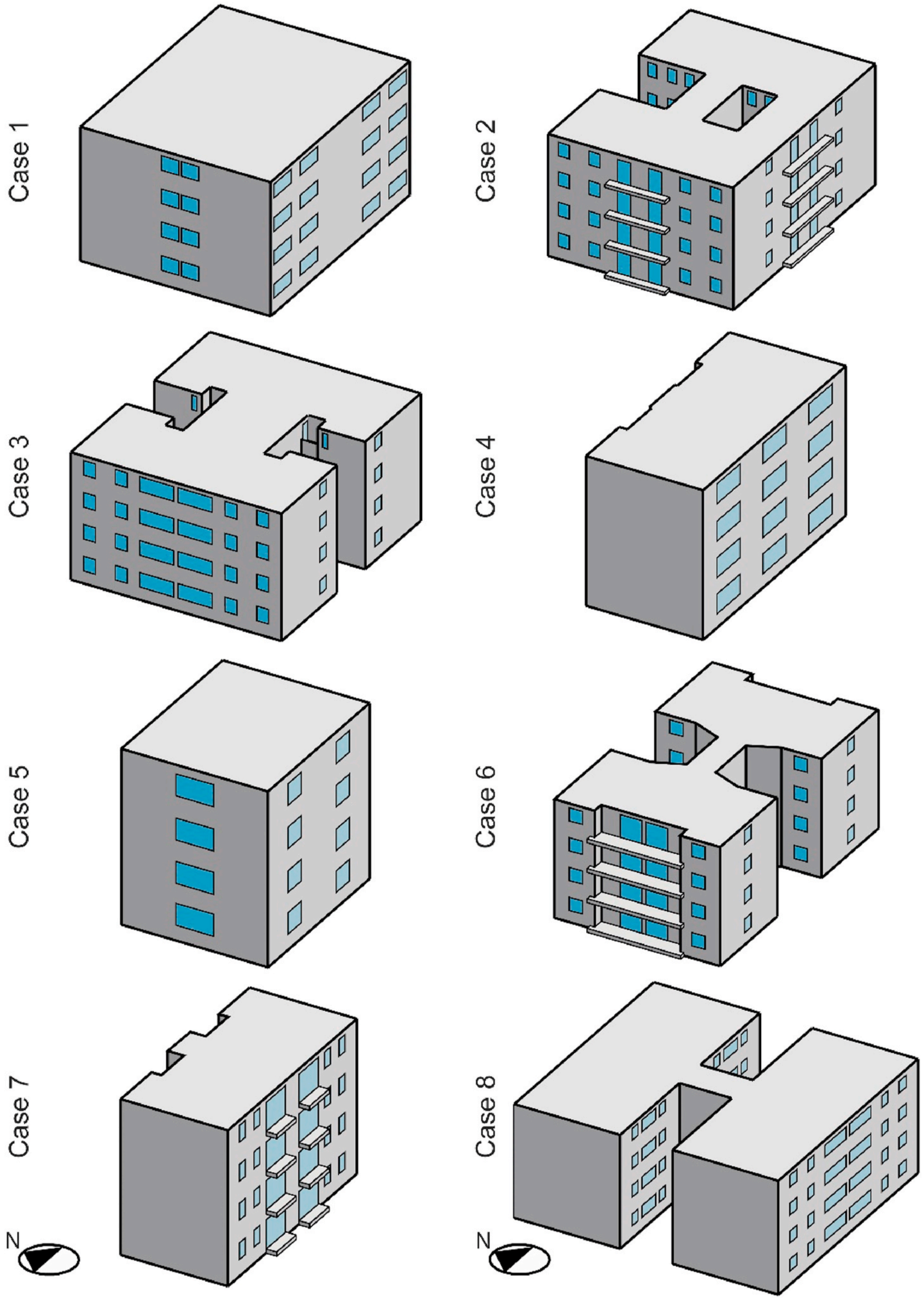


Fig. 2. Case studies analysed in the research.

tations do not depend on the external conditions [69]. A use period of heating equipment is established between October and May (with setpoint temperatures of 17 and 20 °C), and a use period of air conditioning between June and September (with setpoint temperatures of 25 and 27 °C). These use periods of HVAC systems coincide with the periods established for the winter and summer months used in the climate zones of the CTE. The variation of the setpoint temperature value depends on the hour of the day. Likewise, the air change per hour (ACH) was defined according to the CTE load profile,. In this regard, the CTE load profile uses natural ventilation in the summer nights (0:00–8:00) of 4 ACH and a mechanical extract ventilation of 0.63 ACH the rest of the year.

The case studies were simulated in the 779 Andalusian towns, and climate data were obtained in each. For this purpose, METEONORM was used to generate the EnergyPlus weather (EPW) files of each location. METEONORM is a tool composed of 8325 weather stations located all over the world. Through these stations, the tool allows spatial interpolations and stochastic meteorological data to be generated [70].

Likewise, this research was aimed to analysing both the climate change effect on the climate classification and the possibility of establishing variations in that classification by using the cluster analysis approach. For this purpose, 3 EPW files were generated in each location: one for the current scenario, another for the year 2050, and another for the year 2100. The two future EPW files were generated with the A2 scenario of the Special Report on Emissions Scenarios (SRES) because it is one of the most unfavourable scenarios [69]. For this purpose, METEONORM uses an average of the 18 climate models included in the 2007 IPCC report. The models are averaged for the periods 2011–2030, 2046–2065, and 2080–2099. Through linear interpolations, METEONORM allows the values of each decade of the 21st century to be obtained. Other tools, such as CCWorldWeatherGen [71] or Advanced WEather GENerator (AWE-GEN) [72], can be used to obtain these sce-

Table 1
Hourly distribution of the loads in the case study.

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

Table 2
Setpoint temperatures used in the case studies.

Setpoint temperature	Months	Hourly ranges			
		0:00–6:59	07:00–14:59	15:00–22:59	23:00–23:59
Heating setpoint temperature	October–May	17	20	20	17
Cooling setpoint temperature	June–September	27	–	25	27

narios. However, METEONORM is the most used for energy simulation analyses in future scenarios existing in the scientific literature [73–76].

The analysis of buildings in the future is a fundamental aspect to analyse the energy performance of the building stock [77]. This becomes important due to buildings' useful life (between 50 and 100 years) [78]. Therefore, a building constructed or rehabilitated today would have a useful life that includes the analysis time of this study (from now until 2100).

Moreover, the A2 scenario presents a very heterogeneous world. This scenario is characterized by a continuous population increase, with economic developments focused on each region [38,41]. An increase between 2 and 5.4 °C is expected in this scenario at the end of the 21st century in comparison with the values at the end of the 20th century. Each case study was simulated in the 779 towns using 3 climate scenarios (current, 2050, and 2100), so the results of this study were based on 18,696 simulations.

3. Results and discussion

First, the distribution of the energy demand values was studied in the analysis zone according to the scenario. Fig. 3 shows the spatial distribution of the average values of heating and cooling energy demand obtained by the case studies. In the current scenario, the energy demand distribution corresponded to the geographic aspects of the region. The western part of the territory was characterized by having the greatest heating energy demand (with a value of 73.26 MWh/year) as the altitude of this zone is greater because of the mountain ranges of the Baetic system. On the other hand, the Guadalquivir Depression had the greatest cooling energy demand, with a maximum value of 51.54 MWh/year. However, the effect expected because of climate change changed the energy demand related to the regions of Andalusia. Thus, the heating energy demand distribution clearly changed, increasing the lowest energy demand range (between 0 and 7.50 MWh/year) in the coastal zones and in the Guadalquivir Depression. In many towns belonging to mountain zones, heating energy demand is expected in 2100 to be like the current one in cities such as Seville. This could be seen in the progressive reduction of both the quartiles and the maximum values of heating energy demand distributions. Between the current scenario and 2050, the quartile values of the distribution were reduced between 15 and 46%, and between 2050 and 2100, they were reduced between 23 and 44%. This implied that the maximum values of the heating energy demand will range between 13.63 and 48.02 MWh/year at the end of the century. The tendency in cooling energy demand was opposed to heating energy demand because climate change increased the former throughout the 21st century. The most affected zone (in the current scenario it corresponded to the Guadalquivir Depression) will be extended to other Andalusian towns. As for the percentage increase values, the quartile values of the cooling energy demand distribution increased between 10 and 28% from the current scenario to 2050, and between 45 and 49% from 2050 to 2100.

Thus, building energy performance is expected to vary significantly. For this reason, the climate zones of the CTE could present limitations in the future scenarios, so more appropriate zone criteria should be available to remove the possible energy inequalities among the various zones. For this purpose, the cluster analysis was performed according to the description in Section 2. The Silhouette index obtained with the cluster analysis was assessed. This analysis used the same number of groups of the CTE for each climate severity: 5 for winter, and 4 for summer. Fig. 4 shows the distributions of the Silhouette index, and Table 3 shows the average values for each cluster. The quality of the clusters was satisfactory. In this regard, the average values of the Silhouette index were greater than 0.45. Moreover, some clusters obtained average values of the Silhouette index greater than 0.6, such as clusters W1 in the 3 scenarios or clusters S2 and S4 in the current scenario. These aspects showed that the allocation of the towns in each cluster was appropriate. Fig. 4 shows that there were no negative values in the Silhouette index. Thus, the distribution of the towns in 5 groups for the periods of heating energy demand and in 4 groups for the periods of cooling energy demand was appropriate.

Thus, there were variations between the classification conducted by the CTE and the zones obtained in this study. Fig. 5 shows the spatial distribution of the climate zones in Andalusia. As indicated in Section 2, the number of groups was adjusted to the groups of winter and summer climatic zones included in the CTE classification (5 for winter and 4 for summer). The nomenclatures of the climate zones obtained in the cluster analyses were organised from lower to greater. Thus, the nomenclature W1 corresponded to the group with the lowest heating energy demand, and the nomenclature W5 to the group with the greatest heating energy demand. The climate zones of the CTE and the new zones were clearly different. It is worth stressing that the CTE does not consider in its regulation that climate zones could vary throughout time (even though the useful life of buildings ranges between 50 and 100 years [78]). This means that, in the current scenario, the building is designed according to the characteristics of the current climate zone, not considering the possible climate modifications that could affect its energy performance. Nonetheless, there were differences between the climate zones of the current scenario and those of the CTE. Thus, the cluster analysis considered that both coastal towns and the towns in the Guadalquivir Depression had similar climate characteristics in the winter season, whereas in the CTE they were divided into zones A, B, and C (Fig. 6). This aspect was found in all the new climate zones obtained with the cluster analysis. Each had towns classified in different zones according to the CTE. Moreover, some aspects were of interest in these relations. In this regard, the two groups corresponding to the zones with the greatest heating energy demand (zones W4 and W5) had in their distribution towns of the climate zones of the CTE with lower winter severity (e.g., zone A or B). This aspect was detected in the summer zones, but the other way round: the climate zones obtained in the cluster analysis corresponded to the lowest cooling energy demand (e.g., S1). The current scenario with future scenarios were compared, and it was found that cluster zones were composed by towns located in the various zones of the CTE. The climate zones of the CTE did not give response to the climate variations that could take place throughout the 21st century, and the buildings designed according to this regulation

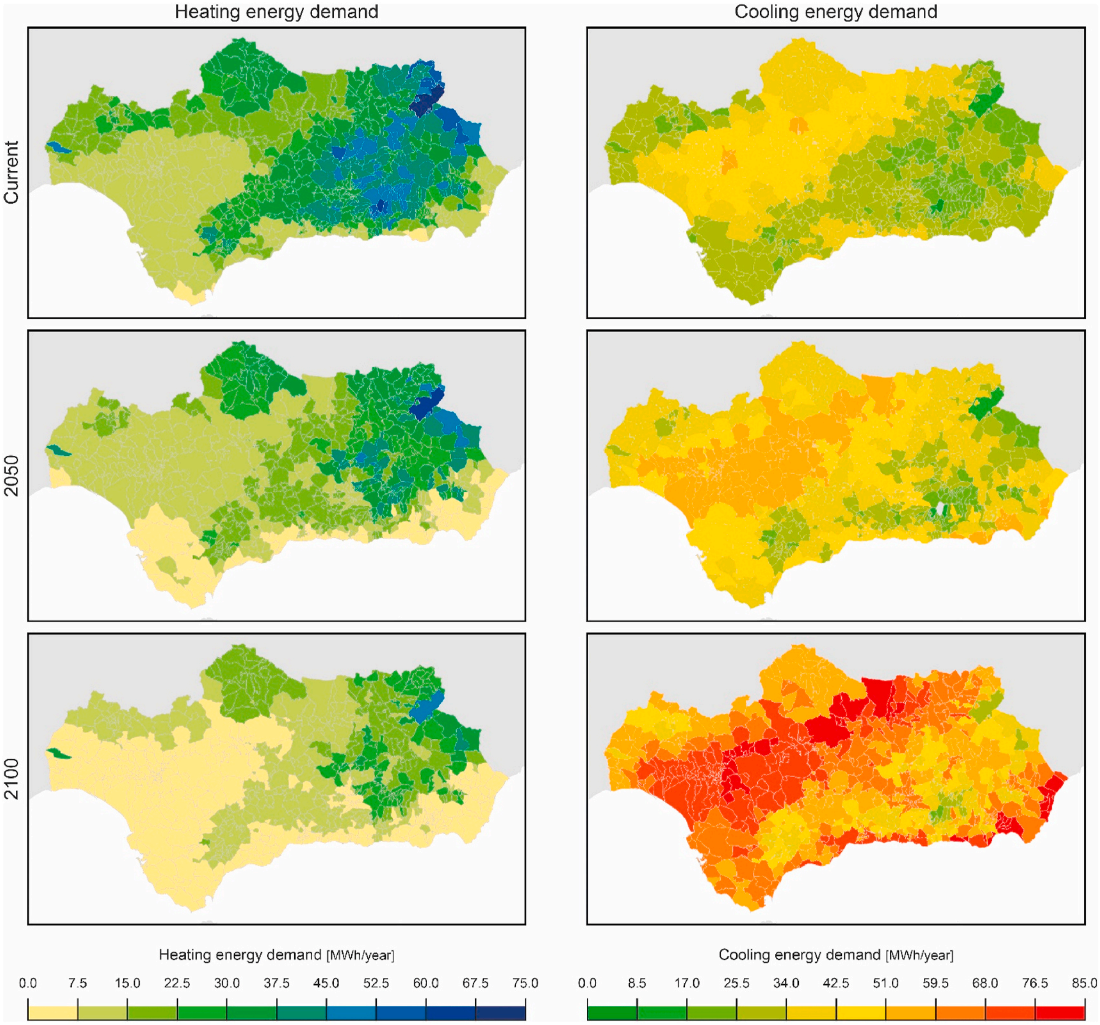


Fig. 3. Average distribution of heating and cooling energy demand in Andalusia in the 3 scenarios analysed.

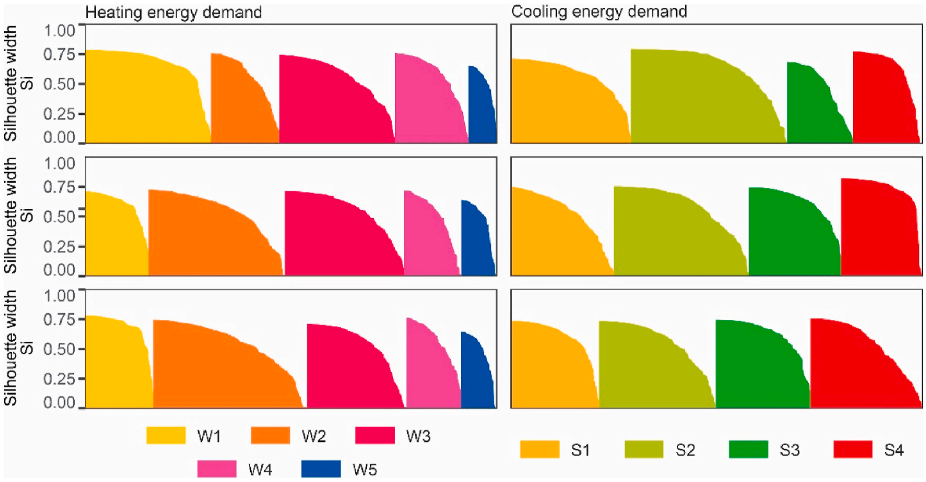


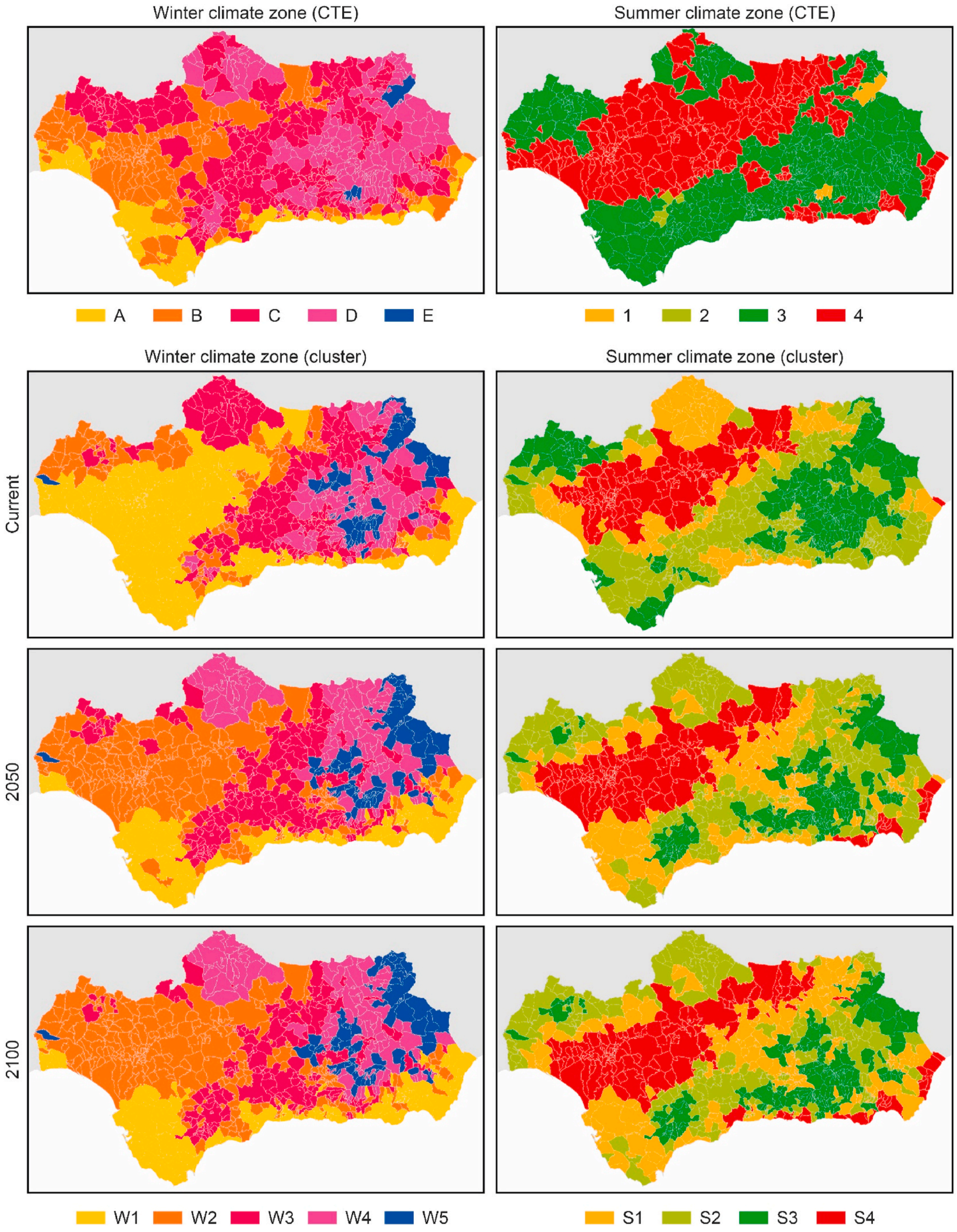
Fig. 4. Values of the Silhouette index in each group obtained with the energy demand data of the current scenario.

could have a low resilience level in the future. Another important aspect is the increase of the number of towns of the severest zones in summer. Zones S3 and S4 progressively increased the number of towns, so zone S3 went from 124 towns in the current scenario to 174 in 2050 and to 179 in 2100, whereas zone S4 went from 127 towns in the current scenario to 153 in 2050 and to 211 in 2100. In the winter zones obtained with the cluster analysis, the reduction of the energy demand varied the distribution of towns per groups due to a greater approach of the centroids of each group.

Thus, there are differences in the groups obtained between the cluster analyses and the CTE. For this reason, the energy demand distributions of each classification were analysed to determine the limitations

Table 3
Silhouette index of the clusters.

Year	Silhouette index								
	Heating energy demand					Cooling energy demand			
	Cluster W1	Cluster W2	Cluster W3	Cluster W4	Cluster W5	Cluster S1	Cluster S2	Cluster S3	Cluster S4
Current	0.68	0.57	0.57	0.59	0.51	0.56	0.63	0.47	0.63
2050	0.60	0.55	0.56	0.51	0.47	0.53	0.58	0.62	0.72
2100	0.67	0.53	0.53	0.55	0.47	0.60	0.56	0.62	0.54

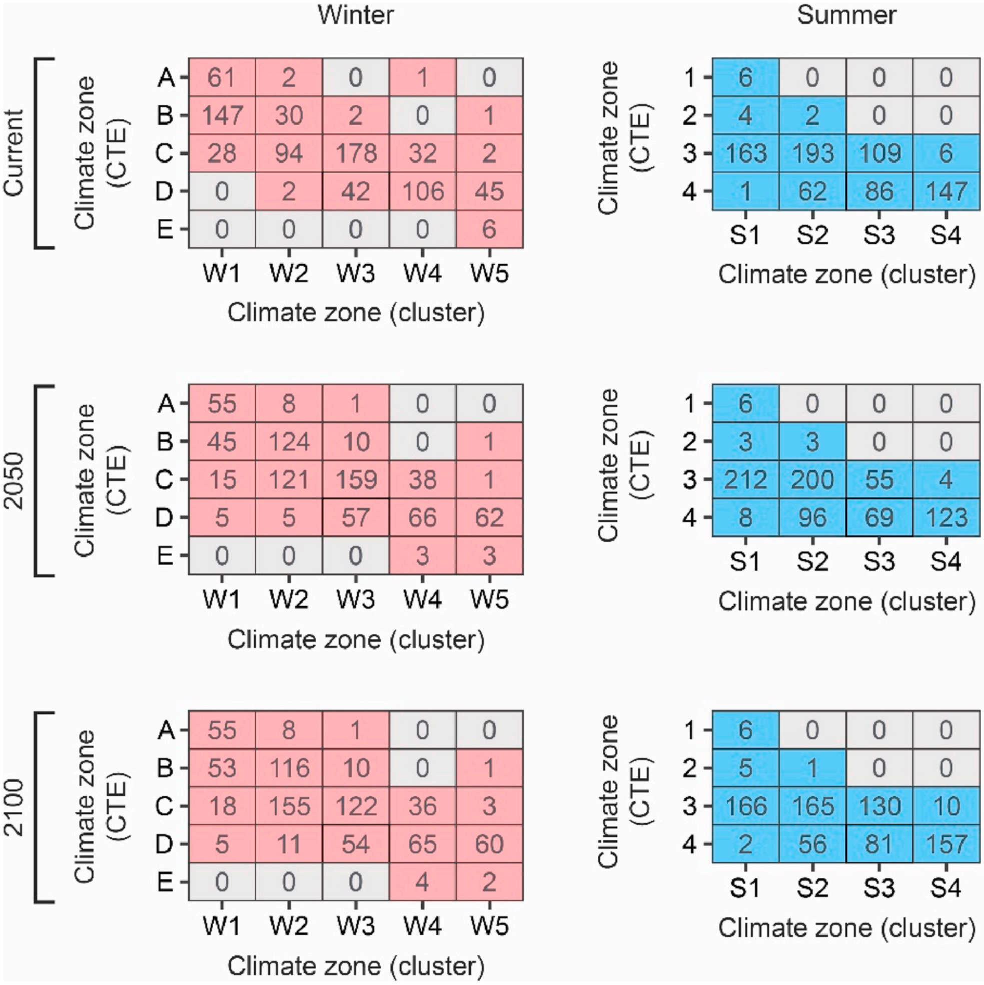

Winter climate zone (CTE)

Summer climate zone (CTE)

Winter climate zone (cluster)

Summer climate zone (cluster)

Fig. 5. Distribution of the climate zones of the CTE and those obtained by the cluster analysis.



Current – Winter

	W1	W2	W3	W4	W5
A	61	2	0	1	0
B	147	30	2	0	1
C	28	94	178	32	2
D	0	2	42	106	45
E	0	0	0	0	6

Current – Summer

	S1	S2	S3	S4
1	6	0	0	0
2	4	2	0	0
3	163	193	109	6
4	1	62	86	147

2050 – Winter

	W1	W2	W3	W4	W5
A	55	8	1	0	0
B	45	124	10	0	1
C	15	121	159	38	1
D	5	5	57	66	62
E	0	0	0	3	3

2050 – Summer

	S1	S2	S3	S4
1	6	0	0	0
2	3	3	0	0
3	212	200	55	4
4	8	96	69	123

2100 – Winter

	W1	W2	W3	W4	W5
A	55	8	1	0	0
B	53	116	10	0	1
C	18	155	122	36	3
D	5	11	54	65	60
E	0	0	0	4	2

2100 – Summer

	S1	S2	S3	S4
1	6	0	0	0
2	5	1	0	0
3	166	165	130	10
4	2	56	81	157

Fig. 6. Distribution matrices of the towns included in each climate zone.

of the two approaches. Figs. 7–12 show the energy demand distributions of each case study according to the type of energy demand and scenario, thus verifying whether there are coincidences among the climate zones, as well as the effectiveness of the classifications. For this study (and to make representative comparisons), the 8 case studies were energy analysed with the same envelope thermal properties in all towns. However, the regulation distinguishes the limit values and the energy demand of the climate zones, thus leading to energy inequalities among regions or zones [38,41]. Having zones with a more appropriate classification would therefore imply a greater control of the limitations of the envelope and guarantee that the fulfilment of the regulation does not arise differences in the energy consumption of a same region. In the current scenario, the heating and cooling climate zones of the CTE were coincident among them: (i) in the winter climate zones of the CTE, the least severe zones (i.e., A and B) had coincidences in the distribution values (e.g., in the case 1, the zone A obtained values of 7.10, 10.69, and 12.10 MWh/year for the first (Q1), second (Q2), and third quartile (Q3), respectively, whereas zone B obtained values of 9.82 MWh/year for Q1, 11.34 MWh/year for Q2, and 14.50 MWh/year for Q3; (ii) in the severest winter zones, the coincidence of the heating energy demand distributions mainly took place between the data lower than the percentile of 25% in a zone and the data between the first and third quartile of the immediately lower zone (e.g., in the case 2, the data of the zone 4 of the percentile of 25% obtained values between 24,205.51 and 36.44 MWh/year, whereas Q1 and Q3 of the zone 3 obtained values of 21.38 and 32.02 MWh/year). There were also coincidences in the distributions between the data from the third quartile and the maximum value in comparison with the data from Q1 and Q3 of the immediately greater zone; and (iii) in the summer zones, the distributions of the zones 2, 3, and 4 were coincident. The distributions between the zones 2 and 3 obtained very similar values (the average differences between the quartile values were between 0.35 and 3.73 MWh/year), whereas the data sample of the percentile of 25% in the zone 4 was coincident with the data sample between Q1 and Q3 in the zones 2 and 3. Except in the zone 1, there was not a clear increase tendency of the cooling energy demand in the cooling zones of the CTE as in the heating climate zones of the CTE.

Two aspects were found for each zone regarding the effect of climate change on the energy demand distributions of each climate zone of the CTE: (i) in winter zones, the heating energy demand reduced the quartile values between 0.76 and 41.21 MWh/year in 2050 and between 0.81 and 67.37 MWh/year in 2100. However, the values of heating energy demand of the distribution of each climate zone were coincident and even that coincidence of the values increased because of both the coincidence of the quartile values of the zones D and E and the increase of the percentile of 25% in most climate zones, reaching minimum values close to 0; and (ii) in cooling zones, the quartile values increased between 2.26 and 4.10 MWh/year in 2050 and between 14.21 and 21.27 MWh/year in 2100. There were also coincidences in the coincidence of data distributions among the summer climate zones of the CTE. These aspects implied possible energy inequalities in the region because the energy efficiency requirements of the CTE are not adapted to the climate characteristics of the region. Moreover, this could be a great challenge for architects and designers due to the possible coincidences among the climate zones. In this regard, the CTE is based on the idea that a building located in a climate zone should have the same en-

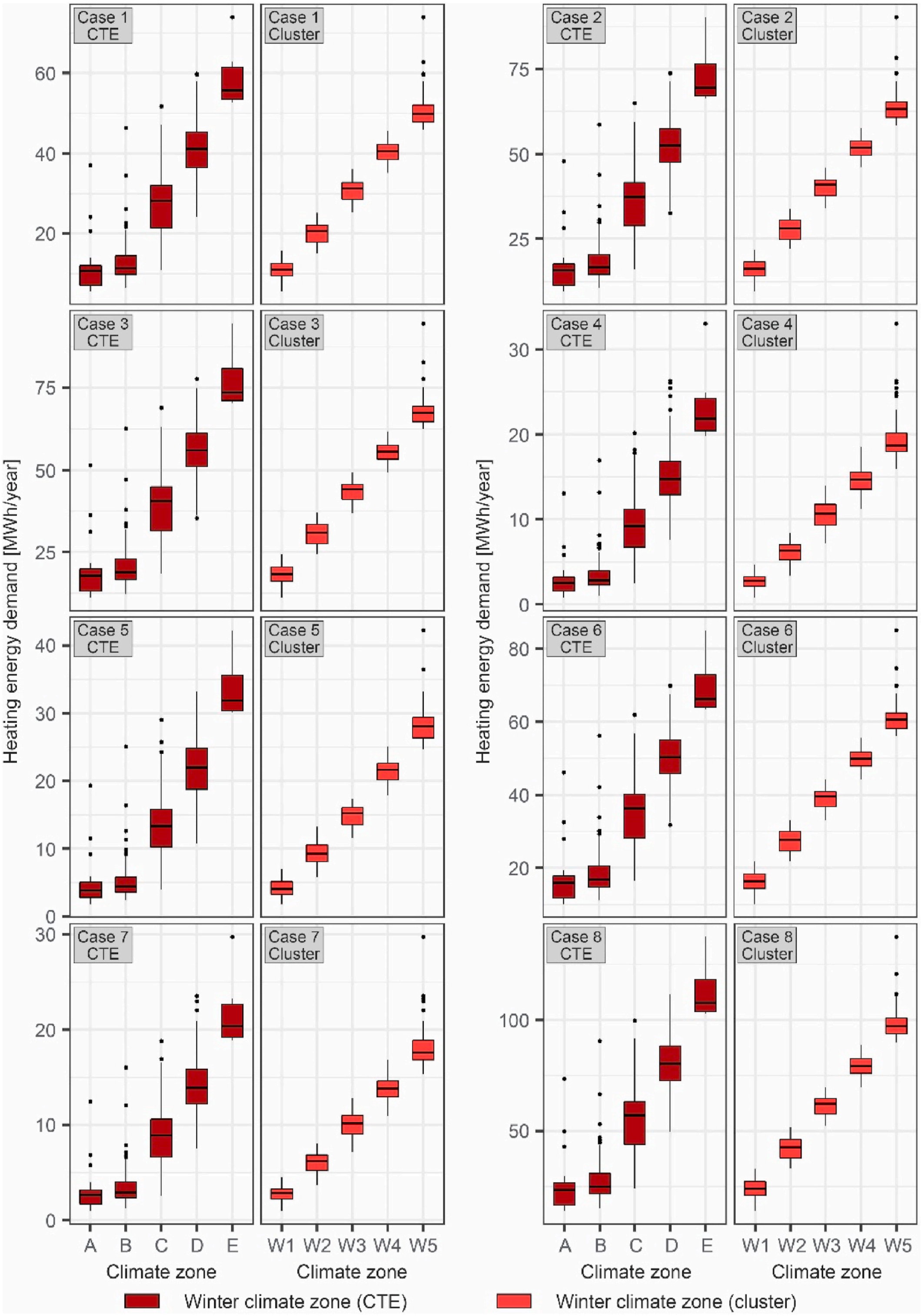


Fig. 7. Boxplots with the distribution of the heating energy demand per winter climate zone in the current scenario.

ergy demand in any location of that climate zone. This criterion of the CTE means that the building stock of various cities (e.g., Seville and Cordoba) should have the same energy performance as they are in the same climatic zone (e.g., B4). However, the results showed towns incorrectly classified (Fig. 13). In the current scenario and according to the case study, the towns incorrectly classified were between 35.815 and 38.511% in the winter zones in the CTE, and between 46.983 and 49.936% in the summer zones in the CTE. Climate change generated that a larger number of towns were incorrectly classified in the winter zones of the CTE (between 44.801 and 46.213% in 2050, and between 46.598 and 50.193% in 2100), whereas the range of towns incorrectly classified was slightly reduced in the summer zones (between 43.902 and 45.186% in 2050, and between 45.828 and 46.470% in 2100).

Given the limitations showed by the climate zones of the CTE, the zones obtained with the cluster analysis could be an opportunity to obtain more consistent groups, with distributions not coinciding but guaranteeing a small number of towns incorrectly classified. The energy demand distributions obtained with the zones of the cluster analysis pre-

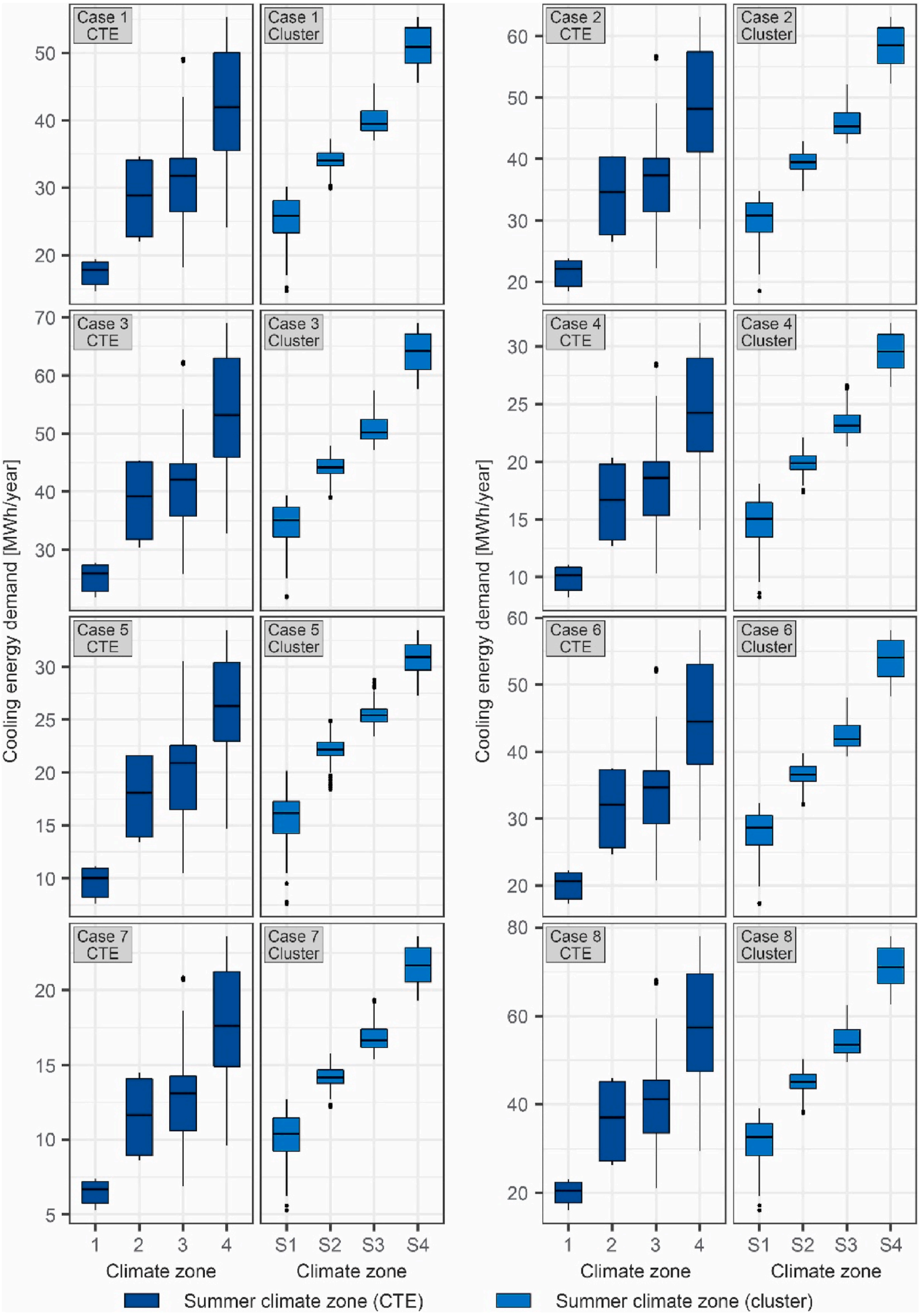


Fig. 8. Boxplots with the distribution of the cooling energy demand per summer climate zone in the current scenario.

sented clear behaviour tendencies (e.g., the increase tendency of the energy demand by going from a W1 to a W5 zone), as well as a low percentage of cases in which there were coincidences in data distributions. By performing a multidimensional cluster analysis considering that each dimension was coincident with a case study, there could be certain group errors in the towns located in the limits of the groups. However, the percentage of towns incorrectly classified was low in comparison with those in the CTE. The cluster analysis obtained percentage values of towns incorrectly classified between 0.128 and 18.742% in heating zones, and between 0.513 and 3.081% in cooling zones (Fig. 13). Most values obtained in the heating zones took place by modifying the climate generated by climate change. This could be verified in the progressive increase of the maximum percentage of towns incorrectly classified, from 7.702% in the current scenario to both 14.249% in 2050 and 18.742% in 2100. These values were obtained in the cases characterized by a low heating energy demand in the current scenario, which was significantly reduced in 2050 and 2100. As there were climate

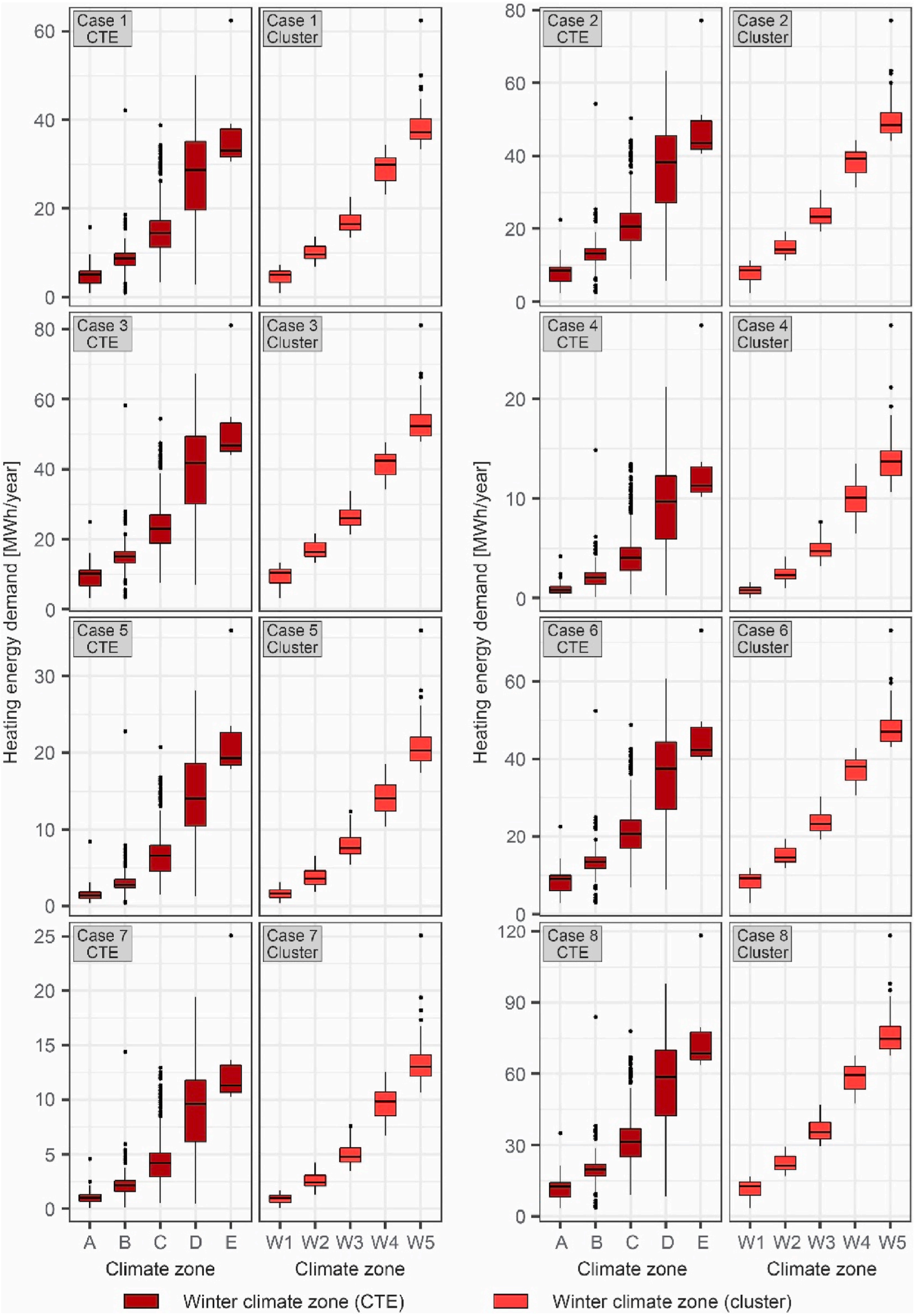


Fig. 9. Boxplots with the distribution of the heating energy demand per winter climate zone in 2050.

zones with centroids of the heating energy demand lower than the other cases, there were limitations to correctly classify the towns.

However, the cluster analysis obtained more consistent climate classifications than those used by the CTE. With these analyses, zones with clear limits of energy demand and with a low interquartile range could be obtained, thus guaranteeing a greater control when establishing limit values adapted to the characteristics of each zone. This aspect could prevent the emergence of energy inequalities in the building stock based on the Spanish regulation. Likewise, considering future scenarios allows modifications to be carried out in the climate zones. This could be of great importance when establishing regulated designs or criteria adapted to climate change by considering the expected variations of the energy demand through the climate zones. A regulation on building energy efficiency considering these aspects could be a most appropriate transition to a low carbon building stock, thus facilitating the fulfilment of the goals set by the European Union for the year 2050.

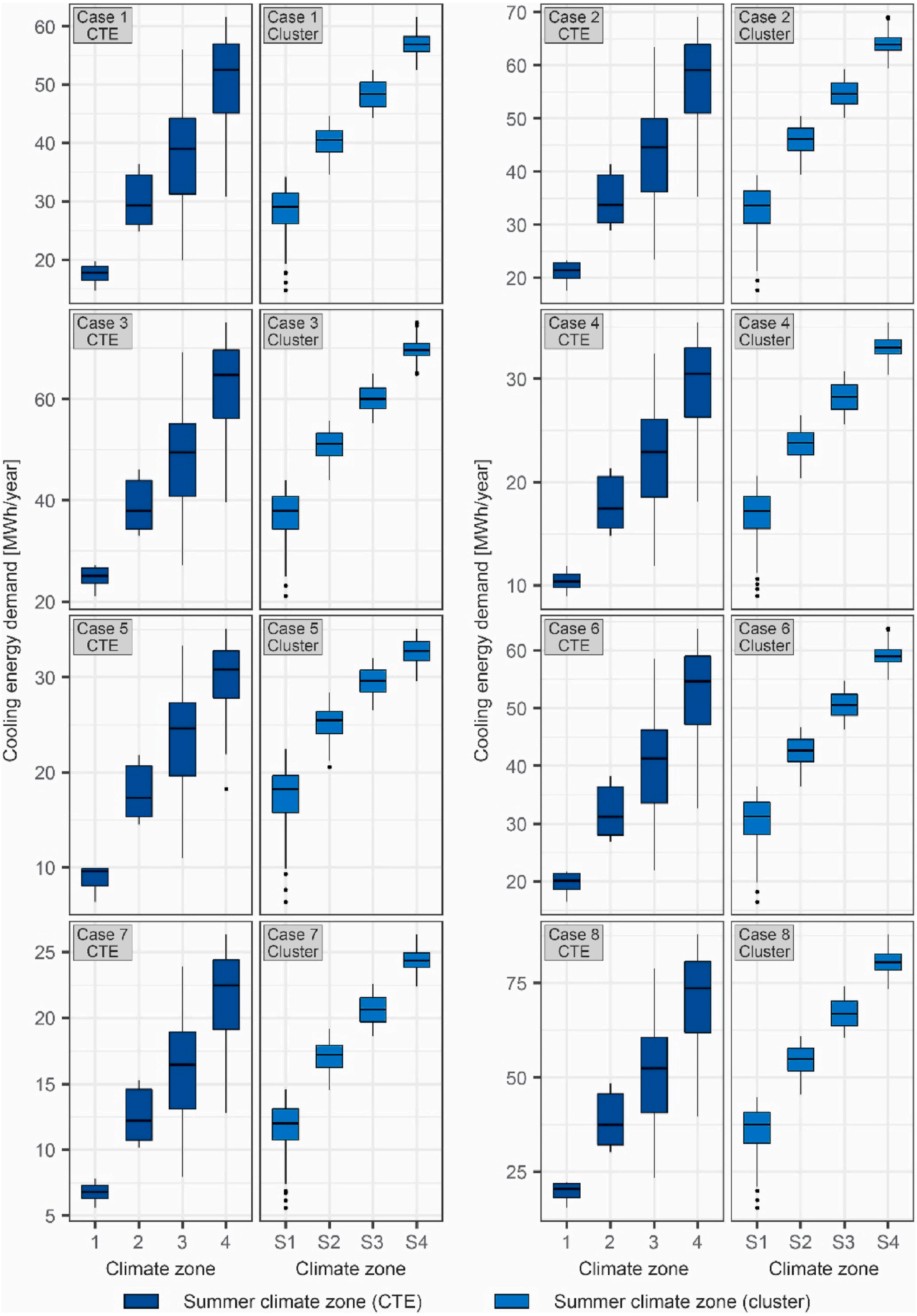


Fig. 10. Boxplots with the distribution of the cooling energy demand per summer climate zone in 2050.

4. Conclusions

This study analysed the limitations of the climate classification of Andalusia in the Spanish Building Technical Code (CTE) in relation to towns incorrectly classified and possible energy inequalities, as well as the potential of using cluster analysis methodologies to obtain the most representative zones. Likewise, the analysis was performed from both current and future climate perspective. According to the results, the following conclusions are drawn:

- The climate zones established by the CTE presented limitations in the energy demand limits related to each zone in the current scenario. Instead of obtaining clear limits, with a different energy demand in each zone, there were coincidences in the energy demand distributions of the various zones. These coincidences took

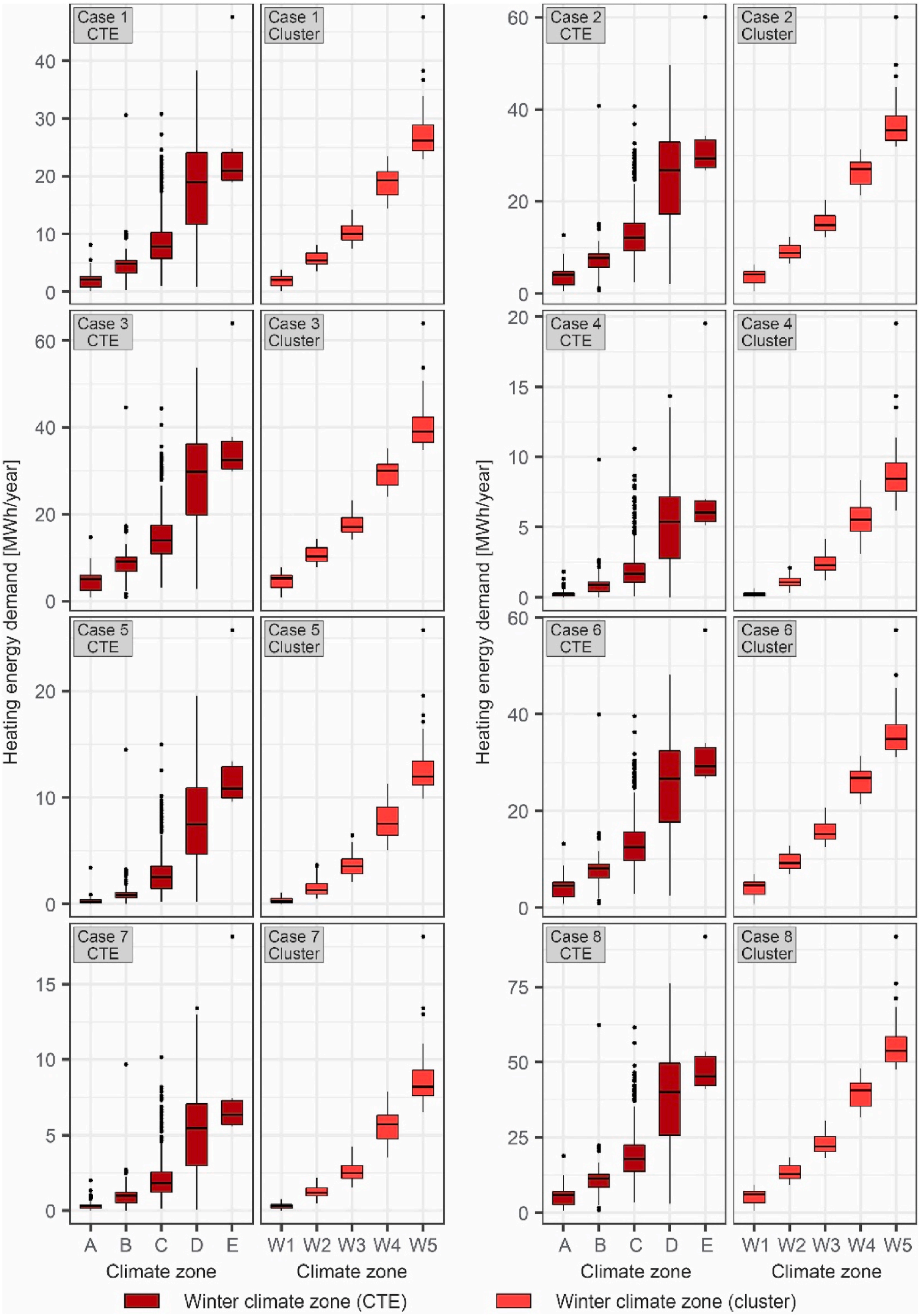


Fig. 11. Boxplots with the distribution of the heating energy demand per winter climate zone in 2100.

place with quartile distribution values. Moreover, there was not an ascending tendency in the energy demand as the winter and summer climate severity increased. Thus, between 35.815 and 49.936% of the Andalusian towns were incorrectly classified using the energy demand data of the case studies. Consequently, the energy demand obtained by the case study in some of these towns was closer to another climate zone than to that of the town.

- Climate change tended to increase these limitations of the climate zones included in the CTE. The climate change analysed in 2050 and 2100 showed an opposed tendency according to the type of energy demand: heating energy demand was considerably reduced in the region, homogenising the energy demand of both coastal zones and the Guadalquivir Depression, and cooling energy demand was increased, also increasing the surface with greater energy demands in hot seasons. These aspects affected the limitations of the climate

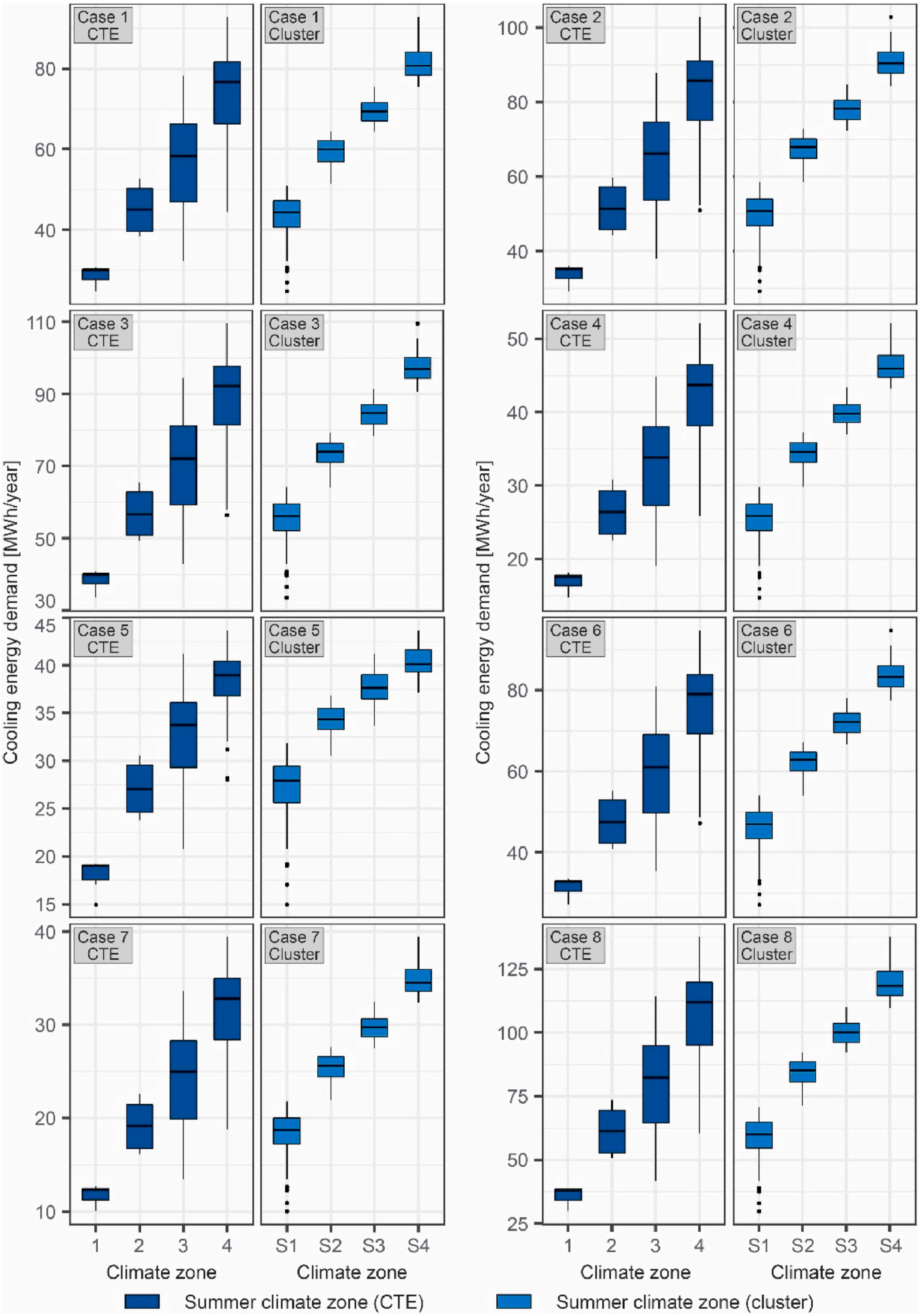


Fig. 12. Boxplots with the distribution of the cooling energy demand per summer climate zone in 2100.

zones in the CTE. As the energy demand varied, the coincidence effect of the energy demand increased among the various climate zones; moreover, there was a greater coincidence of the data distributions in some zones in which that coincidence was not so high as in the current scenario (e.g., the zones D and E). This meant that climate zones were less effective to establish homogeneous zones of building energy performance. This aspect was clearly showed in the increase of the percentage of towns incorrectly classified, increasing in the winter climate zones (between 44.801 and 50.193%) and obtaining similar values in the summer climate zones.

- The cluster analysis obtained climate classifications with clear centroids and limits, guaranteeing the level of independence and difference among the various clusters. The results showed that the groups generated with k-means obtained appropriate silhouette index values (values greater than 0.45 in most of the groups). In addition, the coincidences among the energy demand distributions of each climate zone did not present coincidences with the others,

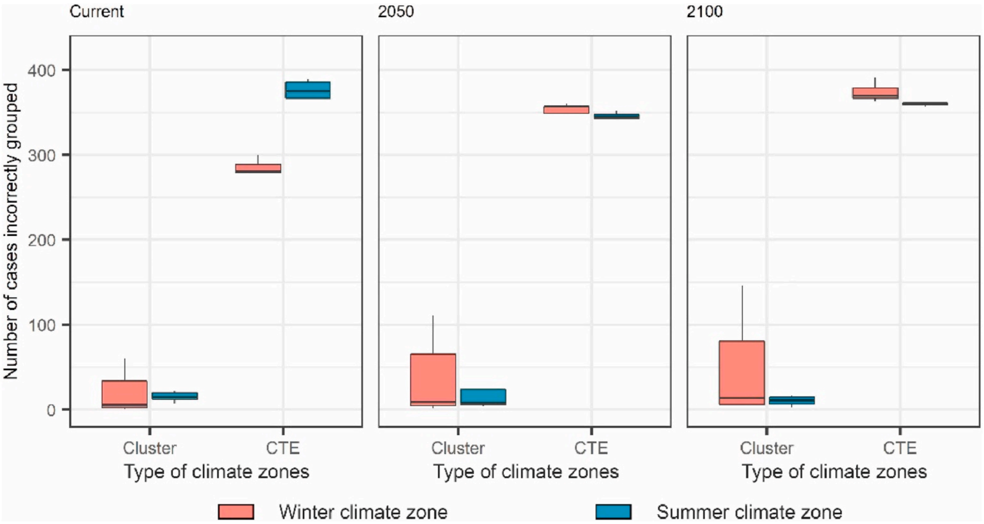


Fig. 13. Distributions with the number of cases incorrectly grouped according to their position with respect to the centroids of the various groups of climate zones.

guaranteeing homogeneous groups with a low interquartile range (particularly in comparison with the zones of the CTE). This can be seen in the percentage of cases incorrectly classified: in the current scenario between 0.128 and 7.702% in the heating zones, and between 0.896 and 2.824% in the cooling zones. Climate change varied the configuration of clusters, thus slighting increasing the percentage of cases incorrectly classified in the heating zones because of the greater number of cases with a very low demand at the end of the 21st century.

Therefore, the results showed the limitations of using the climate zones of the CTE to establish building design criteria and technical specifications. According to the CTE, the energy demand in a climate zone is similar in the whole territory of the same climate zone. However, this study has shown the limitations by existing many coincidences among the various zones. Moreover, these aspects could contribute to the emergence of energy inequalities in the building stock built according to the current regulation as there are variations caused by climate. In this regard, the CTE establishes limit values that vary according to the climate zone. A most appropriate classification could be used to establish new limit values more adapted to each zone and to guarantee that there are no significant energy deviations among the cities in a same region. In this regard, the cluster analysis is an opportunity to establish more appropriate climate zones. In Andalusia, the effectiveness of the new climate zone has been verified, as well as its possible adaptation to future climate variations. These results are of great interest to develop new measures focused on building energy efficiency and sustainability in the medium and long term according to the climate tendencies expected for the 21st century. With a more appropriate regulation, the low-carbon goals set by the European Union for 2050 could be achieved. Nonetheless, some limitations should be addressed in future research works. First, this study is based on Andalusia. Although this region is of great interest due to both the combination of social and economic aspects and the characteristics of the building stock, the analysis should be performed with other towns in Spain. And second, appropriate limit values of the envelope thermal properties should be established for the new climate zones, thus guaranteeing a low energy demand which is similar among the climate zones. Finally, the use of different algorithms to perform cluster analyses should also be studied, thus assessing the variations obtained according to the algorithm.

CRediT authorship contribution statement

David Bienvenido-Huertas: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **David Marín-García:** Conceptualization, Investigation, Formal analysis, Writing – original draft. **Manuel J. Carretero-Ayuso:** Visualization, Investigation, Validation. **Carlos E. Rodríguez-Jiménez:** Visualization, Investigation, Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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