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An innovative approach to assess the limitations of characterizing solar gains in buildings: A Spanish case study

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ABSTRACT

A minimal energy demand should be required in buildings both to optimize the performance of the building façade and to control solar gains. According to the existing studies and national standards, the climate zone classification is usually based on both the degree-days methodology and outdated climate data, thus managing HVAC systems inappropriately or leading to users' thermal discomfort in indoor spaces. To evaluate the current limitations and to characterize solar gains in the Spanish building stock, an innovative approach is presented. For this purpose, seven clustering algorithms were implemented by distinguishing between winter and summer seasons during the calculation procedures. Solar irradiation from 8,948 locations in Spain were used. Likewise, the control of solar gains was analysed with the regulatory approach of Spain and with those developed through the study. The results of this research revealed that climate zones set by the Spanish Technical Building Code could imply to use values of monthly accumulated solar irradiation with discrepancies between 43.17 and 84.41 kWh/m^2, compared to the real values. Hence, an accurate method focused on k-means clustering should be adopted. Furthermore, the results can be used for a more accurate analysis of solar control and improve the energy efficiency of buildings.

1. Introduction

1.1. State of the art

Climate change is changing society operation in the first decades of the 21st century. It potentially impacts on biosphere's habitability conditions [1], thus stressing the loss of glaciers, fauna and flora extinction, and the great risk of the disappearance of coastal cities. These consequences are the result of the high greenhouse gases (GHG) emitted by society, increasing the external temperature. The energy consumption of the built environment is a major contributor to GHG emissions. Most of the built environment has two characteristics [2,3]: (i) deficient performance because of their design; and (ii) the use of non-renewable energy sources. As a result, significant data of the building impact have been obtained. As for the European Union, the statistics show that the building stock is responsible for up to 40% of the energy consumption of the region [4,5], as well as for 36% of GHG emissions [6,7]. This situation, together with that of other sectors, has led to establish decarbonisation goals based on the Paris Agreement [8]. The European Union has also established a roadmap towards a low-carbon economy by 2050 [9].

For this purpose, the European Union has developed various guidelines that urge member states to adopt measures. Most guidelines focus on the building envelope improvement as façades greatly impact building energy consumption [10,11]. The importance of building envelope characteristics, such as thermal insulation [12] and air tightness [13], has been widely stressed. However, the control of solar gains could significantly impact on the energy demand as well [14,15]. This impact is not limited to common use of buildings, such as residential or office buildings. Even in religious buildings, where solar gains could influence up to 55% on the energy demand [16]. Therefore, most studies focus on this mentioned aspect, as reported below. Weber et al. [17] analysed the use of exoskeletons for the solar control in high-rise buildings. The design achieved savings of up to 48% through exterior shading. Paneri et al. [18] reviewed the existing solutions in transparent insulation (TI)

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Nomenclature

A3	climate zone of the Spanish Building Technical Code. The winter climate severity is A and the summer climate severity is 3.
A4	climate zone of the Spanish Building Technical Code. The winter climate severity is A and the summer climate severity is 4.
ARX	autoregressive-exogenous.
$A_{building}$	useful surface area of the indoor spaces of the building.
$A_{w;p}$	surface of the window.
B3	climate zone of the Spanish Building Technical Code. The winter climate severity is B and the summer climate severity is 3.
B4	climate zone of the Spanish Building Technical Code. The winter climate severity is B and the summer climate severity is 4.
C1	climate zone of the Spanish Building Technical Code. The winter climate severity is C and the summer climate severity is 1.
C2	climate zone of the Spanish Building Technical Code. The winter climate severity is C and the summer climate severity is 2.
C3	climate zone of the Spanish Building Technical Code. The winter climate severity is C and the summer climate severity is 3.
C4	climate zone of the Spanish Building Technical Code. The winter climate severity is C and the summer climate severity is 4.
CTE	Spanish Building Technical Code.
D1	climate zone of the Spanish Building Technical Code. The winter climate severity is D and the summer climate severity is 1.
D2	climate zone of the Spanish Building Technical Code. The winter climate severity is D and the summer climate severity is 2.
D3	climate zone of the Spanish Building Technical Code. The winter climate severity is D and the summer climate severity is 3.
DD_S	mean degree-days in summer.
DD_W	mean degree-days in winter.
E1	climate zone of the Spanish Building Technical Code. The winter climate severity is E and the summer climate severity is 1.
E	east.
F_F	frame fraction.
$F_{sh;obst}$	reduction factor for the external shading obstacle.
GHG	greenhouse gases.
$g_{gl;sh;wi}$	total solar energy transmittance of the glazing with the movable shading device activated.
$g_{gl;wi}$	total transmittance of solar energy of the glazing with the movable shading device deactivated.
$H_{tot;jul}$	mean accumulated solar irradiation of July.
$H_{tot;monthly}$	monthly accumulated solar irradiation of the month analysed.
N	north.
NE	northeast.
NW	northwest.
N_{TOT}	number of maximum hours of sun.
n	number of hours of sun.
$q_{sol;jul}$	control solar.
$q_{sol;gl;sh;wi}$	characterization of solar gains in all the months of the year.
$q_{sol;gl;wi}$	characterization of solar gains with and without the movable shading devices activated.
S	south.
SCS	summer climate severity.
SE	southeast.
SW	southwest.
TI	transparent insulation.
UPGMA	unweighted pair group method with arithmetic mean.
W	west.
WCS	winter climate severity.
WPGMA	weighted average linkage.

systems, stressing the use of polypropylene and cellulose acetate. Wang et al. [19] developed a window with specular reflection of venetian blind, achieving savings of 78,8 $kWhm^2$ in warm months. In addition, there are more and more solutions that integrate photovoltaic devices in the glasses and shading elements, allowing to reduce solar gains and generate electricity [20].

Apart from the importance of the building envelope, the urban environment is also crucial in the energy demand related to solar gains [21,22], since it could be reduced up to 50% depending on the urban density [23]. By way of example, the use of solar gain in cold regions could be interesting. Some designs, such as the Trombe Wall [24], reduce heating energy demand. Nevertheless, an excessive overheating could affect users' thermal comfort. To avoid these isolated situations, Brideau et al. [25] determined the effectiveness of using cold pipes and thermal storage tanks.

Likewise, most studies were based on improving procedures to characterize the solar irradiation used in building energy assessments. In the last decade, one of the first studies was conducted by Kuhn et al. [26], who assessed the possibility of using a methodology to simulate complex façades. In another similar study, Wang and Chen [19] developed a model to determine the solar gains of a multi-glazing façade with venetian blind of specular reflection. This model had an appropriate adjustment degree in comparison with experimental results. Zhang et al. [27] developed a model to estimate solar gains by using an autoregressive-exogenous (ARX) model, and limited measurement data were required to use it. Rasmussen et al. [28] computed non-parametric methods through B-splines to determine the relationship between solar gains and the solar irradiation measured. As a result, the effects generated by close shading obstacles were accurately studied in several case studies. Characterizing solar gains in buildings could be a challenging task, such as the case of highly glazed buildings [29]. Likewise, some studies have stressed the importance of using input variables related to direct and diffuse radiation to estimate thermal and/or energy variables of buildings. Hollick et al. [30] combined lumped thermal capacitance models with Bayesian methods to estimate building performance. Direct and diffuse solar radiation were used. Likewise, Evola and Marletta [31] determined a solar response factor to estimate the building cooling load.

The characterization methods of solar radiation and the control of building envelope features are being increasingly included in the standards of each country. In Spain, the modification of the Spanish Building Technical Code in 2019 established a criterion to control solar gains through the passive design of buildings [32]. The procedure is based on estimating solar gains in a simplified way by implementing ISO 52016-1 [33], so the standard is easily used by architects and engineers. To determine the value of the monthly accumulated solar irradiation, the regulation uses the average values of the climate zones established for the winter and summer months. A climate zone is defined as areas of the same country that are similar in terms of environmental conditions considered in the analysis. Many countries use climate zones to define the characteristics that buildings must meet. However, the method used for classification can be very different [34]. In the case of Spain, climate classification is based on heating degree days and cooling degree days. Consequently, there may be differences in other climate variables, such as radiation. In this sense, previous studies have reported the existing limitations with this approach, although these studies have focused on other aspects. Días-López et al. [35,36] reported the limitations that climatic zones may present in the future. The action of climate change could lead to significant variations in the climatic zones of Spain, obtained with data that is currently out of date. Bienvenido-Huertas et al. [37,38] reflected the inequalities in energy demand in the built environment based on the criteria of thermal insulation and climatic zones established by the Spanish Building Technical Code.

1.2. Aim of this study

Thus, previous studies have shown the limitations associated with the climatic zones of the Spanish Building Technical Code. The limitations are related to both the procedure to obtain climate zones (based on degree-days and using outdated climate data) and the emergence of energy inequalities by establishing regulatory thermal insulation values. However, the limitations related to the solar control process included in the standard have not been studied. One of the goals of this study was therefore the assessment of these limitations. Through this objective, it was possible to assess the error associated with the use of simplified criteria based on climate zones for the characterization of solar gains. Likewise, this study focused on establishing a more optimal climate classification to estimate building solar gains, so simplified calculation procedures could be more accurately obtained to be used the professionals of the sector.

Finally, the international importance of the goals presented in the study should be stressed. Climate classifications are available for most countries of the European Union to regulate the characteristics of the envelope of new and restored buildings [34]. Using inappropriate climate classification criteria could inefficiently control solar gains. In this sense, there are no studies in the scientific literature that have addressed the relationship between buildings, climatic zone and solar control. Likewise, many countries are lacking an advanced regulation on building energy efficiency, and their first climate classifications are being developed [39]. The results expected in this study could be useful for countries, either with or without a developed regulation, to set the next steps to improve their building energy regulations.

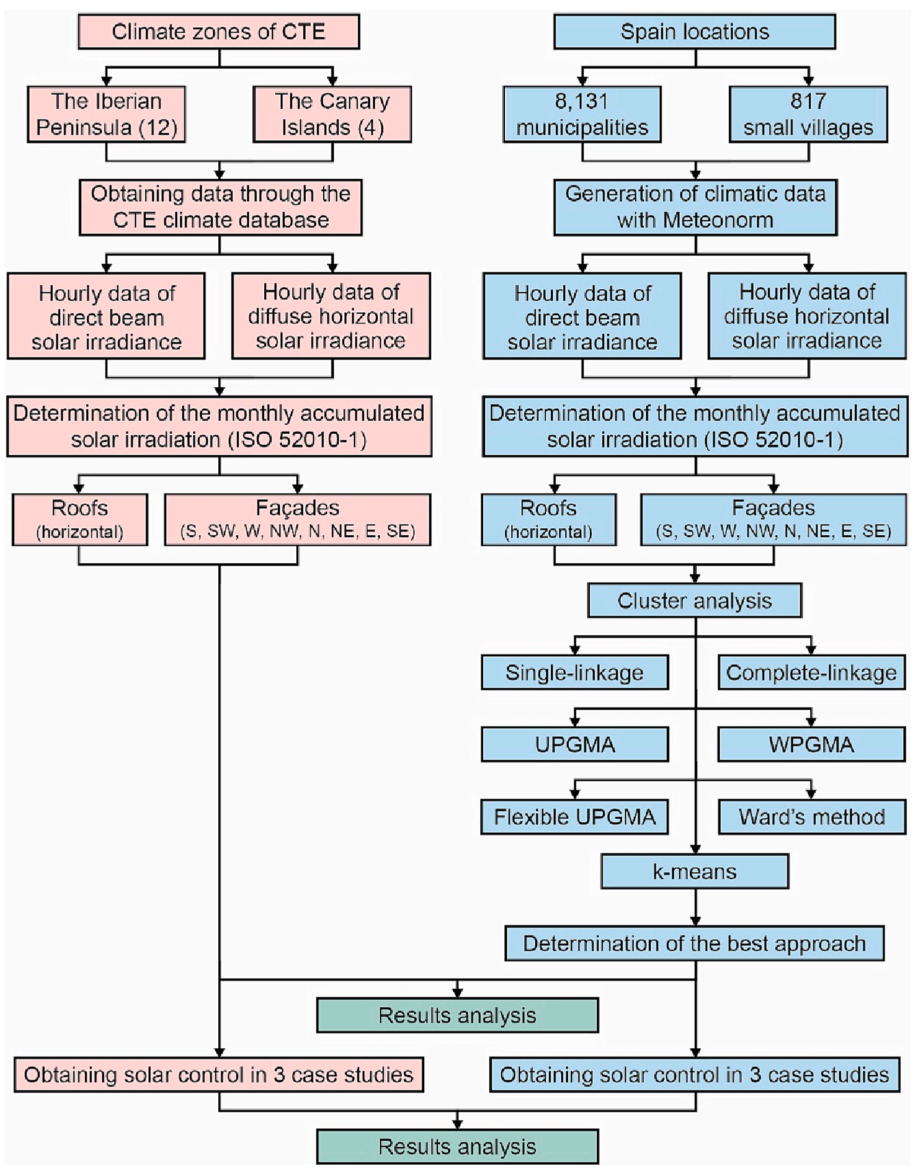

Fig. 1. Flowchart of the procedure followed in this research.

2. Methodology

The research methodology is shown in Fig. 1. The framework consisted of obtaining climatic data both from two approaches, the climatic zones of the Spanish Building Technical Code (CTE) and from all locations in Spain (8131 municipalities and 817 villages). After gathering these data, the monthly accumulated solar irradiation values were computed according to ISO 52010–1. Subsequently, cluster analysis was carried out with the data from all the locations. In this way, solar control outcomes could be estimated for 3 case studies considering both approaches. The obtained results were assessed and compared among them. It should be pointed out that the following subsections provide detailed information on the quantitative analysis.

2.1. Analysing solar gains with the Spanish Building Technical Code

There are many cities and villages in Spain. For their administrative organisation, most cities are called municipalities and are divided into provinces and autonomous regions. Indeed, 8,131 municipalities can be distinguished in Spain, and some of them are isolated cores known as districts, which implies a urban core with building stock. As regards building energy efficiency, the Spanish Building Technical Code (CTE) [40] sets out the requirements that both new buildings and the performances in existing buildings should meet, taking into account the heterogeneity of the climate. Along this line, two different classifications are established: one for winter (based on the concept of winter climate severity (*WCS*)), and another for summer (based on the concept of summer climate severity (*SCS*)). A letter between A and E is given to *WCS* (α could be an option for the Canary Islands), and a number between 1 and 4 is given to *SCS* (Table 1). Combining *WCS* and *SCS* allows 15 various climate zones to be obtained (Fig. 2). Both *WCS* and *SCS* are obtained through linear correlations compared to the mean degree-days with the base of 20 °C:

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

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

where DD_W and DD_S is the mean degree-days in winter (between October and May) and in summer (between June and September), respectively; and $\frac{n}{N_{TOT}}$ is the quotient between the number of hours of sun (n) and the number of maximum hours of sun (N_{TOT}) from October to May.

The CTE was modified in 2019, to include the control of solar gains through building envelopes [32]. As seen in (Eq. (1), solar control ($q_{sol;jul}$) is the relationship between the solar gains for July through the envelope windows with movable solar protection activated and the useful surface area of the building. This indicator involves the heat flow by solar gains of ISO 52016-1 [33], not considering the sky irradiation but the movable solar protection activated. The solar control value for July is limited to 2 kWh/m^2·monthly for private residential buildings, and to 4 kWh/m^2·monthly for the remaining buildings.

Table 1
Winter and summer climate classes according to the CTE.

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

$$q_{sol;jul} = \frac{\sum_{i=1}^{n} F_{sh;obst} \bullet g_{gl;sh;wi} \bullet (1 - F_F) \bullet A_w \bullet H_{tot;jul}}{A_{building}} \quad (3)$$

where $F_{sh;obst}$ is the reduction factor for the external shading obstacle; $g_{gl;sh;wi}$ is the total solar energy transmittance of the glazing with the movable shading device activated; F_F is the frame fraction; $H_{tot;jul}$ is the mean accumulated solar irradiation of July; $A_{w;p}$ is the surface of the window; and $A_{building}$ is the useful surface area of the indoor spaces of the building. Most of the variables used in the calculation depend on building features and location climate data, except $H_{tot;jul}$. To make the work of architects and engineers easier, the CTE provides the mean values of the monthly accumulated solar irradiation by orientation for each climate zone (distinguishing between the Iberian Peninsula and the Canary Islands (Table 2).

These values of the monthly mean accumulated solar irradiation were estimated by using the referential climate files of each climate zone of the CTE (which were obtained according to *WCS* and *SCS*) and by applying ISO 52010-1 [41]. This standard adopts calculation procedures developed by Perez et al. [42,43]. The geographic coordinates of the location (latitude, longitude, and altitude), the direct beam solar irradiance, and the diffuse horizontal solar irradiance are used to determine the accumulated irradiation used for the calculations of ISO 52016-1 (e.g. solar gains as $q_{sol;jul}$). The coordinates of the climate zones are always the same, making a distinction according to whether the location is in the Iberian Peninsula or in the Canary Islands (Table 3). The geometry of the Perez model is therefore the same in the climate files of the CTE, except whether its location is in the Canary Islands.

2.2. Data acquisition

The procedure of the CTE is simple. It simplifies solar irradiation data according to the climate zones and the geometry of Perez's model. A total of 8,948 Spanish locations were selected, including 8,131 municipalities and 817 districts and small villages. Hourly data of both direct beam solar irradiance and diffuse horizontal solar irradiance of these locations were gathered by using METEONORM 8.1. This software is made up of 8,325 weather stations placed all over the planet. Its use has been supported by several studies [44–47]. The data from these stations can be used to generate climate datasets of any location through a stochastic process [48]. To generate these datasets, both the temperature period between 2000 and 2019 and the radiation period between 1996 and 2015 were selected.

Based on these radiation data, ISO 52010-1 was applied. The values of the monthly accumulated solar irradiation were determined for all the months of the year, for horizontal (roofs) and vertical surfaces (façades) in the following orientations: north, south, east, west, north-west, south-west, north-east, and south-east. In addition, some assumptions were adopted: a solar reflectivity of the ground of 0.2 (like the CTE), a solar constant of 1,370 W/m^2, and a value of 1,014 rad^{-3} for the constant parameter for clearness formula.

To compare the irradiation models of the CTE, all locations (8,948) were classified according to its climate classification. For this purpose, the ranges by province established in the CTE were used to determine the climate zone of locations according to their altitude (Fig. 3). By way of example, a location at an altitude of 600 m in Albacete has climate zone D3. The simplifications established by the CTE for the coordinates of each zone were used to calculate the accumulated solar irradiation of all the months of the year in the various surfaces/orientations. This was conducted because, as indicated in Subsection 2.1, the CTE only indicates the centroids of July.

2.3. Cluster analysis

2.3.1. Algorithms

A total of 7 algorithms of classification were implemented to assess

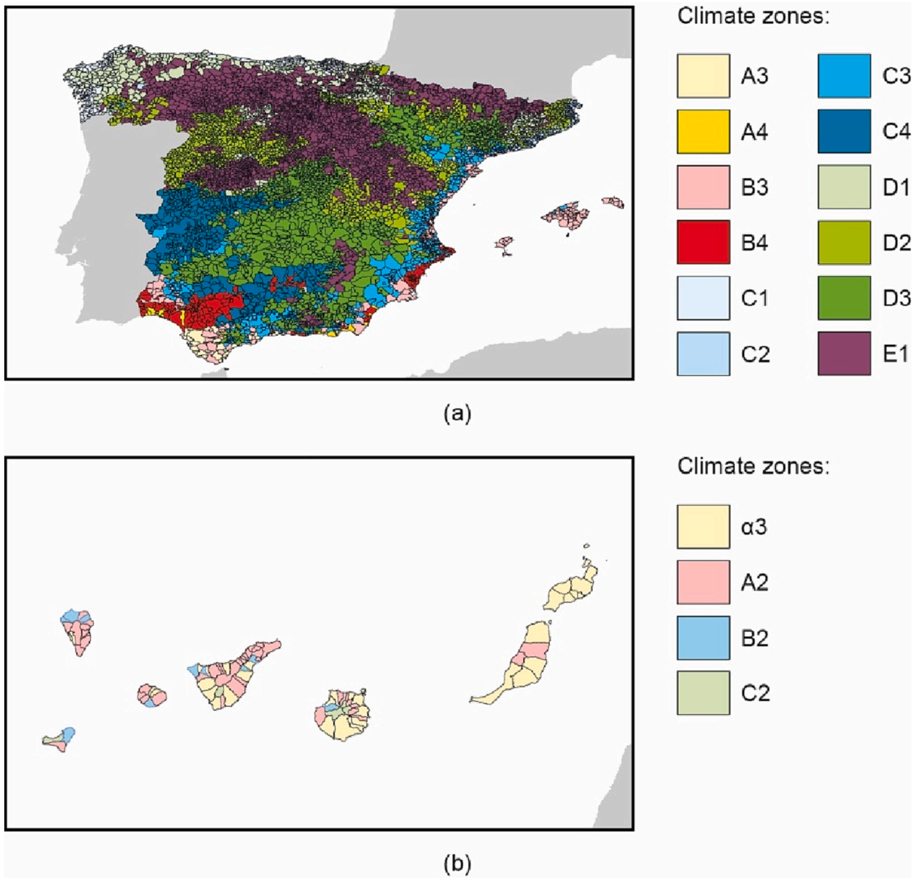

Fig. 2. Climate zones included in the Spanish Building Technical Code (CTE): (a) Iberian Peninsula and (b) Canary Islands.

Table 2
The accumulated solar irradiation values established by the CTE for each climate zone.

Variable	Climate zone	Mean accumulated solar irradiation in July (kWh/m^2)								
		Horizontal	NE	E	SE	S	SW	W	NW	N
The Iberian Peninsula	A3	220.36	96.73	127.81	117.82	89.53	115.84	124.70	94.30	59.39
	A4	235.35	99.25	132.86	123.70	94.78	123.83	133.97	100.69	61.12
	B3	220.33	92.03	121.85	114.45	89.73	114.64	122.02	92.07	57.92
	B4	235.31	101.70	135.64	125.09	94.13	121.94	131.14	94.48	61.00
	C1	195.77	88.49	114.47	106.12	81.72	101.55	108.06	84.00	56.85
	C2	217.19	96.61	128.05	117.89	88.17	111.22	118.78	90.17	58.23
	C3	220.34	97.05	128.62	118.69	89.37	115.69	125.22	95.24	59.61
	C4	235.35	101.78	136.41	126.01	94.84	121.68	130.08	97.16	60.36
	D1	195.80	88.53	114.54	106.15	81.96	101.33	107.19	82.96	56.51
	D2	217.18	94.76	125.48	116.31	88.51	113.39	121.59	92.18	58.27
	D3	220.32	94.22	124.81	116.03	89.15	115.91	125.24	94.95	58.91
	E1	195.79	88.95	114.88	106.34	82.09	101.16	106.71	82.58	56.67
The Canary Islands	α3	220.11	101.98	121.50	96.44	56.30	95.45	119.73	100.47	63.76
	A2	216.93	100.05	119.62	95.52	52.26	91.60	113.03	94.66	61.64
	B2	216.90	98.20	116.52	92.9	55.18	94.02	118.23	99.50	62.80
	C2	216.91	101.03	119.95	94.85	55.33	91.94	114.83	96.70	63.06

Table 3
Coordinates related to the climate zones of the CTE.

Location of the climate zone	Longitude	Latitude	Altitude	Time zone
The Iberian Peninsula	−4.133333	40.683331	667	+1
The Canary Islands	−16.366659	28.325001	30	0

the most effective cluster. From these algorithms, 6 were hierarchical cluster algorithms (single-linkage, complete-linkage, unweighted pair group method with arithmetic mean –UPGMA-, weighted average linkage -WPGMA-, flexible UPGMA, and Ward's method) and 1 was a non-hierarchical cluster algorithm (k-means).

The single-linkage algorithm creates clusters from bottom to top [49]. Along this line, all observations start in individual clusters that are combined until obtaining just one cluster. Closer clusters are combined in each phase (Eq. (4)). In other words, the single-linkage algorithm measures the similarity of the most similar couple, so the algorithm is known as the nearest neighbour clustering method. However, the complete-linkage algorithm is based on that the similarity of any two clusters is the similarity of the most different couple of individuals (Eq. (5)) [49]. This is also known as the farthest neighbour clustering

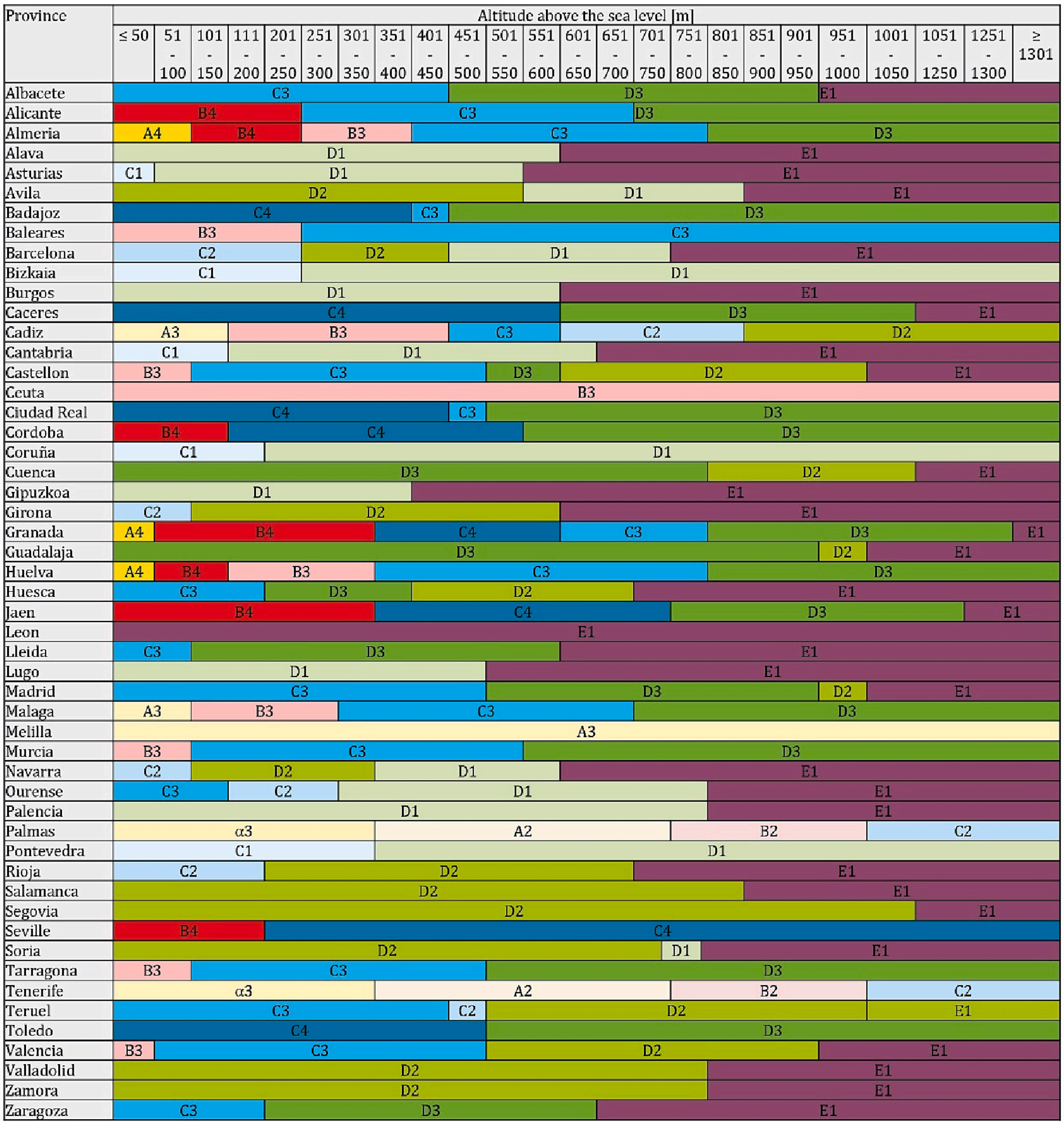

Fig. 3. Matrix of the climate classification of the Spanish Building Technical Code according to the altitude of each province. The climatic zone of the locations of each province is determined by altitude.

method.

$$D(X,Y) = \min_{x \in X, y \in Y} d(x,y) \tag{4}$$

$$D(X,Y) = \max_{x \in X, y \in Y} d(x,y) \tag{5}$$

where X and Y are the two clusters analysed.

UPGMA [50] works by progressively combining individual clusters using the average distance among couples of individuals between two clusters (Eq. (6)). Thus, the distance of combining clusters with new clusters will be achieved from the proportional average of the new distances (Eq. (7)). WPGMA is a similar option to UPGMA [50]. In this case, the distance with new clusters results from the average of distances with the new cluster (Eq. (8)).

$$\frac{1}{|X| \bullet |Y|} = \sum_{x \in X} \sum_{y \in Y} d(x,y) \tag{6}$$

$$D(X \cup Y, Z) = \frac{|X| \bullet d_{X,Z} + |Y| \bullet d_{Y,Z}}{|X| + |Y|} \tag{7}$$

$$D(X \cup Y, Z) = \frac{d_{X,Z} + d_{Y,Z}}{2} \tag{8}$$

Flexible UPGMA modifies the original algorithm [51]. For this purpose, the formula by Lance-Williams is used to determine the differences of the clusters created with others (Eq. (9)). The values of α_1 and α_2 are proportional to the size of the clusters (Eq. (10)). A value of −0.1 is used for β, according to the recommendations by Belbin et al. [51].

$$D(X \cup Y, Z) = \alpha_1 \bullet D(X,Z) + \alpha_2 \bullet D(X,Z) + \beta \bullet D(X,Y) + \gamma \bullet [D(X,Z) - D(Y,Z)] \tag{9}$$

$$\alpha_j = \alpha'_j \bullet \frac{|X|}{|X| + |Y|}$$

$$\alpha'_j = 1 - \beta$$

$$-1 \le \beta < 1 \tag{10}$$

The last hierarchical method was the Ward method [52]. This method uses an objective function to establish the couple of clusters to join. The algorithm therefore detects the couple of clusters that could be merged with a minimum increase in the total variance. For this purpose, the Euclidean distances squared is used.

Finally, the k-means algorithm is the non-hierarchical algorithm used in this study. This algorithm is based on a X sample of n observations divided into k clusters, for which a W partition of that sample is considered with $W = (w_1, \cdots, w_a, \cdots, w_b, \cdots, w_k)$, so that $\left(\bigcup_{a=1}^{k} w_a = X, w_a \cap w_b = \emptyset, \mathrm{a} \neq \mathrm{b}\right)$, with the total sum of the sums of squares of the Euclidean distances within each cluster being minimum:

$$\underset{W}{\operatorname{argmin}} \sum_{a=1}^{k} \sum_{x_i \in w_a} \sum_{r=1}^{p} (x_{ir} - \mu_{ar})^2 \quad (11)$$

The stages of the k-means algorithm are as follows: (i) the number of k clusters used for the analysis is identified; (ii) k individuals of the dataset, which will be the initial centroids, are randomly selected; (iii) the association measurement is used to calculate the distance of each individual to each k centroid; (iv) k clusters are formed by assigning each individual to the closest centroid; (v) the new centroids of each k cluster are identified; and (vi) Stages 3 and 4 take place again. This last stage could lead to two situations: Stage 5 starts if in Stage 4 some of the individuals change the cluster, so the cycle is repeated, or the cluster analysis finishes when no individual changes the cluster in Stage 4.

2.3.2. Approach used for the cluster analysis

The input variables of this cluster analysis were the mean accumulated solar irradiation both in horizontal and vertical surfaces in the orientations considered in this study (as indicated in Subsection 2.2). Each variable was pre-processed to normalise data for the cluster analysis (i.e., the variables were rescaled between 0 and 1). The accumulated solar irradiation was different in winter and summer seasons, so two classifications were conducted for each season, according to the current climate classification of the CTE. Given the significant difference of the Canary Islands in comparison with the Iberian Peninsula, classifications were conducted for both regions. Table 4 summarises the number of clusters, which oscillated between 2 and 20 in the Iberian Peninsula, and between 2 and 16 in the Canary Islands.

After making up the clusters, the best combination to reduce the deviation in comparison with the actual values was determined. For this purpose, the analysis was based on simple indicators, such as the deviation in comparison with the actual value (Eq. (12)), the average deviation in comparison with the actual value (Eq. (13)), and the percentage of municipalities with greater error with the CTE in comparison with that obtained with the cluster analysis (Eq. (14)).

$$Deviation = a_i - c_i \quad (13)$$

$$Deviation\ average\ decrease = \frac{\sum_{i=1}^{n} (a_i - c_i)}{n} \quad (14)$$

$$Percentage\ with\ \ greater\ error\ with\ CTE = 100 \frac{\sum_{i=1}^{n} CTE_i}{n}$$

Table 4
Number of clusters.

Algorithm	Number of clusters			
	The Iberian Peninsula		The Canary Islands	
	Winter season	Summer season	Winter season	Summer season
Single-linkage	20	20	16	16
Complete-linkage	20	20	16	16
UPGMA	20	20	16	16
WPGMA	20	20	16	16
Flexible UPGMA	20	20	16	16
Ward's method	20	20	16	16
K-means	20	20	16	16

$$if\, CTE_i > cluster_i;\ \ CTE_i = 1$$

$$if\, CTE_i \leq cluster_i;\ \ CTE_i = 0 \quad (15)$$

where a_i is the actual value of the accumulated solar irradiation (value of the location), c_i is the value of the accumulated solar irradiation provided by the centroid of the cluster, n is the number of locations, and CTE_i is a value of 0 or 1 obtained by the rules indicated in Eq. (15)).

2.4. Case studies

The final goal of this study was the analysis of the existing limitations of the assessment procedure of solar gains of the CTE and the approach of a new methodology for more accurate characterizations. Regardless of the variations of the accumulated solar irradiation in climate, the differences expected in the values of solar gains of buildings were assessed. For this reason, a total of three case studies that correspond to residential buildings were used (Fig. 4). These three buildings have similar geometry characteristics, with three floors each. Solar gains were calculated by the simplified procedure of ISO 52016–1 shown in the CTE. As mentioned above, this procedure is based on the calculation of solar gains with the shading devices activated in July. This approach does not allow to characterize the building behaviour throughout the year, so 2 modifications were tested: (i) the characterization of solar gains in all the months of the year ($q_{sol;gl;sh;wi}$); and (ii) the characterization of solar gains with and without the movable shading devices activated ($q_{sol;gl;wi}$). Eq (16) shows the procedure to estimate solar gains with the movable shading devices activated in July, and Eq. (17) with the movable shading devices deactivated.

$$q_{sol;gl;sh;wi} = \frac{\sum_{i=1}^{n} F_{sh;obst} \bullet g_{gl;sh;wi} \bullet (1 - F_F) \bullet A_w \bullet H_{tot,monthly}}{A_{building}} \quad (16)$$

$$q_{sol;gl;wi} = \frac{\sum_{i=1}^{n} F_{sh;obst} \bullet g_{gl;wi} \bullet (1 - F_F) \bullet A_w \bullet H_{tot,monthly}}{A_{building}} \quad (17)$$

where $g_{gl;wi}$ is the total transmittance of solar energy of the glazing with the movable shading device deactivated; and $H_{tot;monthly}$ is the monthly accumulated solar irradiation of the month analysed.

$F_{sh;obst}$ and F_F were assessed in all the windows of the case studies. A total of three different glazing typologies, which are common in most of the Spanish built environment, were considered (Table 5). Likewise, the movable shading device were pastel blinds.

Each case study was placed in the 8,948 locations. Moreover, three different characterizations were conducted in each location according to the values of accumulated solar irradiation used: actual values of the location, values of the centroids of the climates of the CTE, and values of the centroids of the classification obtained by the analysis cluster. Therefore, the total set of combinations of case studies was 79,596.

3. Results and discussion

First, the differences in the monthly accumulated solar irradiation were analysed by using the current approach of the CTE. By way of example, Fig. 5 shows the differences in the values of the accumulated solar irradiation in July in the Iberian Peninsula, and Fig. 6 shows those in the Canary Islands. As indicated in the Methodology section, the analysis was individually performed in these two areas of the country because of the existing differences in the solar irradiation due to their longitudes and latitudes. July, as mentioned above, is the month that controls the passive design requirements established by the CTE. There were clear differences between the actual values of the accumulated solar irradiation of each municipality and the average value assigned according to the climate zone of the CTE. In this regard, the values of accumulated solar irradiation in the Iberian Peninsula, some orientations (east, west, and north), and horizontal surface areas usually

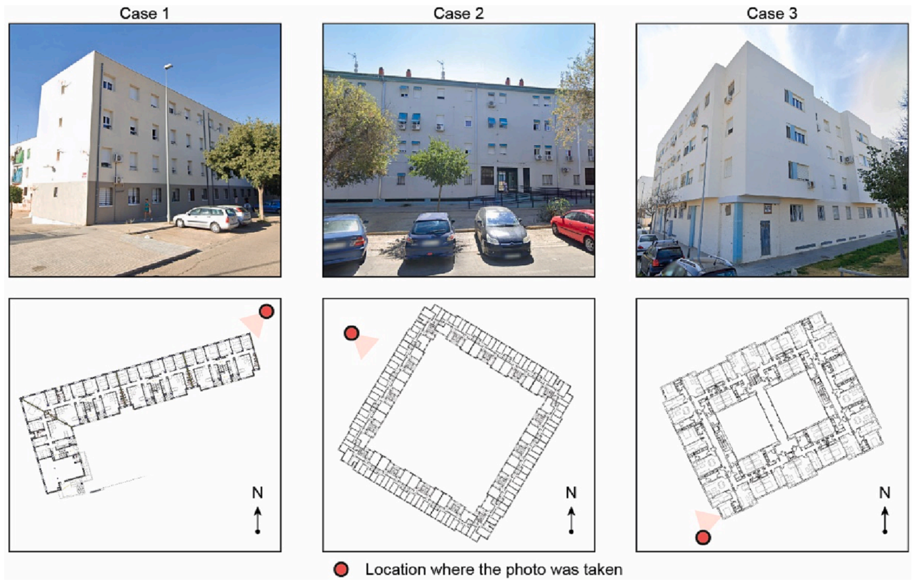

Fig. 4. Case studies used in the research for the analysis of solar gains. The plans indicate the location where the photo was taken.

Table 5
Envelope typologies and total transmittance value of solar energy.

Envelope	Glazing	$g_{gl;wi}$	$g_{gl;sh;wi}$
Envelope 1	Simple	0.77	0.11
Envelope 2	Double	0.68	0.08
Envelope 3	Double low-emissive	0.60	0.05

obtained the lowest values by the climate zone criterion of the CTE. This underestimates the actual effect of the solar irradiation on the building energy consumption in the Iberian Peninsula. As for the Canary Islands, lower values of solar irradiation were given for north and south orientations in July. In contrast, east and west orientations obtained both greater and lower deviations than the centroids of the CTE. As a result, this first assessment showed that the values established by the CTE for the accumulated solar irradiation in July are not appropriate to assess the effectiveness of the passive design of the building (as it is carried out today).

Nevertheless, the analysis based on the differences in all the territory was not enough because of two reasons: (i) the lack of accurate knowledge of the existing differences in the accumulated solar irradiation; and (ii) the behaviour throughout all the year. The latter is significant because both the CTE and ISO 52016-1 establish the possibility of performing monthly analyses to assess the positive effect of heat gains in heating periods, as well as the negative effect in cooling periods (e.g. through the control parameters of shading devices). Fig. 7 shows the distributions of the deviation of the solar irradiation in each month of the year by orientation in the whole territory of Spain (the Iberian Peninsula and the Canary Islands). Considering first the warmest months, the distributions showed absolute deviations between 1.66 and 28.76 kWh/m^2 in the quartile values, whereas the maximum deviation values ranged between 18.73 and 61.42 kWh/m^2. These differences took place according to the orientation analysed. As Figs. 5 and 6 show, orientations are crucial for the existing differences. As for the summer months, both east and west orientations, as well as horizontal surface areas, were characterized by obtaining the greatest deviations in the quartile distribution values: (i) east and west orientations obtained deviation values between −19.54 and −43.17 kWh/m^2 in the minimum values, between −4.9 and 25.38 kWh/m^2 in the quartiles, and between 32.6 and 64.12 kWh/m^2 in the maximum values; and (ii) the horizontal surface areas obtained deviation values between −17.55 and −53.34 kWh/m^2 in the minimum values, between −3.4 and 28.76 kWh/m^2 in the quartiles, and between 40.44 and 58.01 kWh/m^2 in the maximum values. In these cases, the percentage deviations in comparison with the average values of the climate zones reached up to 35%. The north orientation was another one where differences were detected in the maps of Fig. 5. There were differences, but the low range of values related to solar irradiation of this orientation led to low deviations: between 0.5 and 10.1 kWh/m^2 in the quartile values, and between 9.58 and 19.1 kWh/m^2 in the maximum values. As for the south orientation, the most adjusted values to the actual ones were detected in the summer months (with a median in the deviation distributions between 2.2 and 6.1 kWh/m^2), although the maximum deviation values reached up to 40.65 kWh/m^2. As for intermediate orientations (south-west, south-east, north-west, and north-east), there was a mix of the several characteristics presented by the deviations of the main orientations: south-west and south-east orientations showed distributions with a median lower than east and west orientations, whereas north-west and north-east obtained marked differences in solar irradiation values, although the lowest interquartile range decreased between 3.7 and 9.88 kWh/m^2 in comparison with east and west orientations. As for the winter months, the differences presented various tendencies. The south orientation in the summer months was characterized by a lower deviation between actual and CTE values; however, in the winter months, this orientation obtained the greatest deviations. This was reflected in the south orientation, but also in south-east and south-west orientations: (i) the south orientation obtained deviations between −40.28 and −30.69 kWh/m^2 in the minimum distribution values, between −3.23 and 28.28 kWh/m^2 in the quartile, and between 68.53 and 84.81 kWh/m^2 in the maximum values; and (ii) the south-east and south-west orientations obtained deviations between −37.89 and −26.75 kWh/m^2 in the minimum distribution values, between −3.02 and 23.03 kWh/m^2 in the quartiles, and between 56.53 and 70.18 kWh/m^2 in the maximum values. These orientations therefore presented deviations of up to 36% in comparison with the values of the climate zones of the CTE. As for the orientations with the greatest deviations in the summer months (east, west, and horizontal surface areas), the differences between the actual and CTE values were lower, an aspect reflected in the medians of the distributions, with values between 2.95 and 8.75 kWh/m^2. As for the north, north-west, and north-east orientations, the deviations presented both a median value close to 0 (between −0.31 and 1.27 kWh/m^2) and a low interquartile range (between 1.74 and 2.9 kWh/m^2). In these orientations the low irradiation related to the winter months implied that the

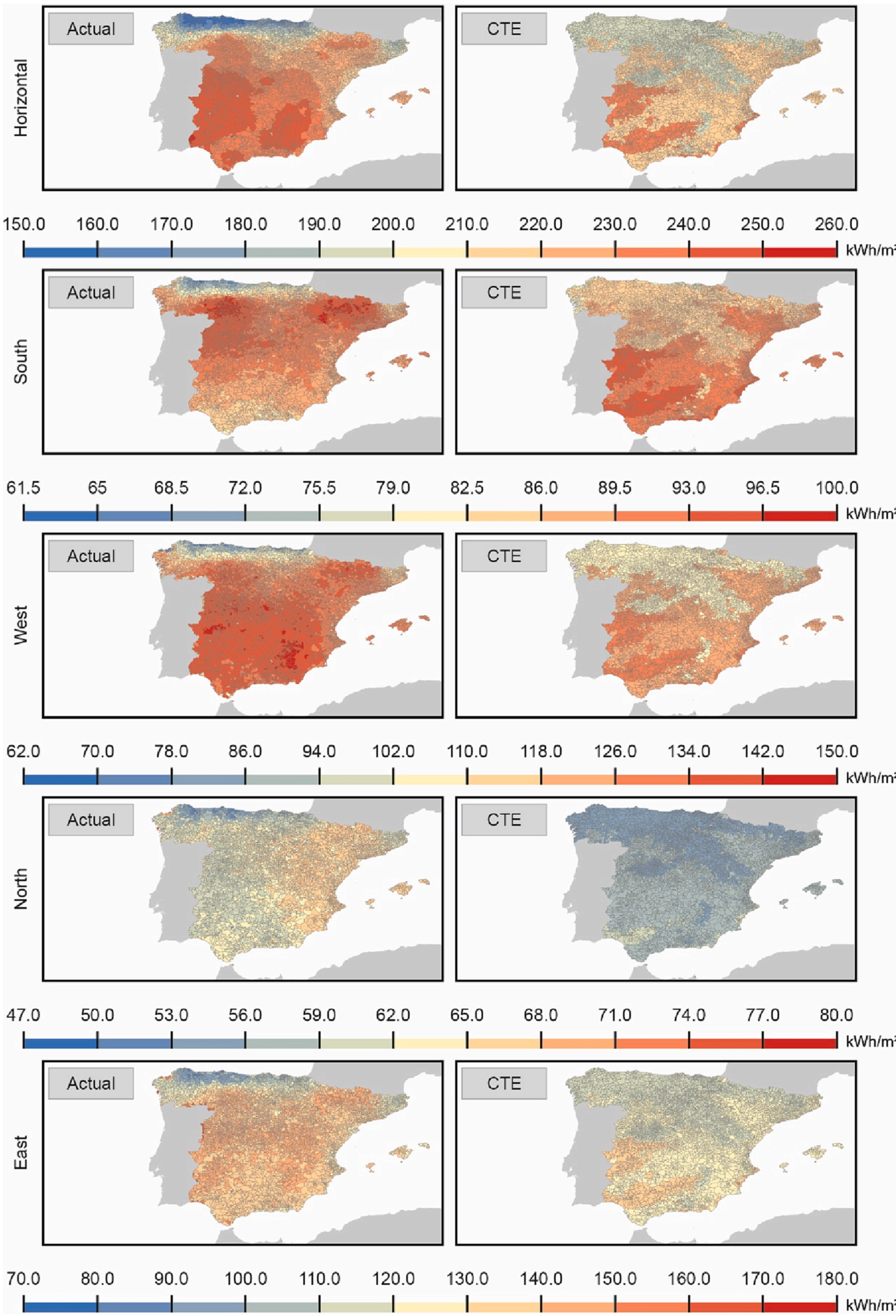

Fig. 5. Comparison between the actual values and the values of the Spanish Building Technical Code (CTE) of the accumulated solar irradiation in July (the Iberian Peninsula and Balearic Islands). The results are shown for façades (south, north, east and west orientations) and roofs (horizontal).

CTE values could be considered as representative. However, in the remaining months-orientations combinations, the results showed deviations that could end in that the results of the energy analysis of buildings were not representative. These deviations also took place in spring and autumn seasons when the tendencies in the winter and summer months were observed.

Hence, the outcomes revealed that the methodology used by the Spanish regulation to characterize and assess solar irradiation is not appropriate. The existing deviations could lead to unrepresentative results in building energy assessments. For this reason, this research presents a new classification of the country. As indicated in the Methodology section, various cluster analyses were conducted, applying

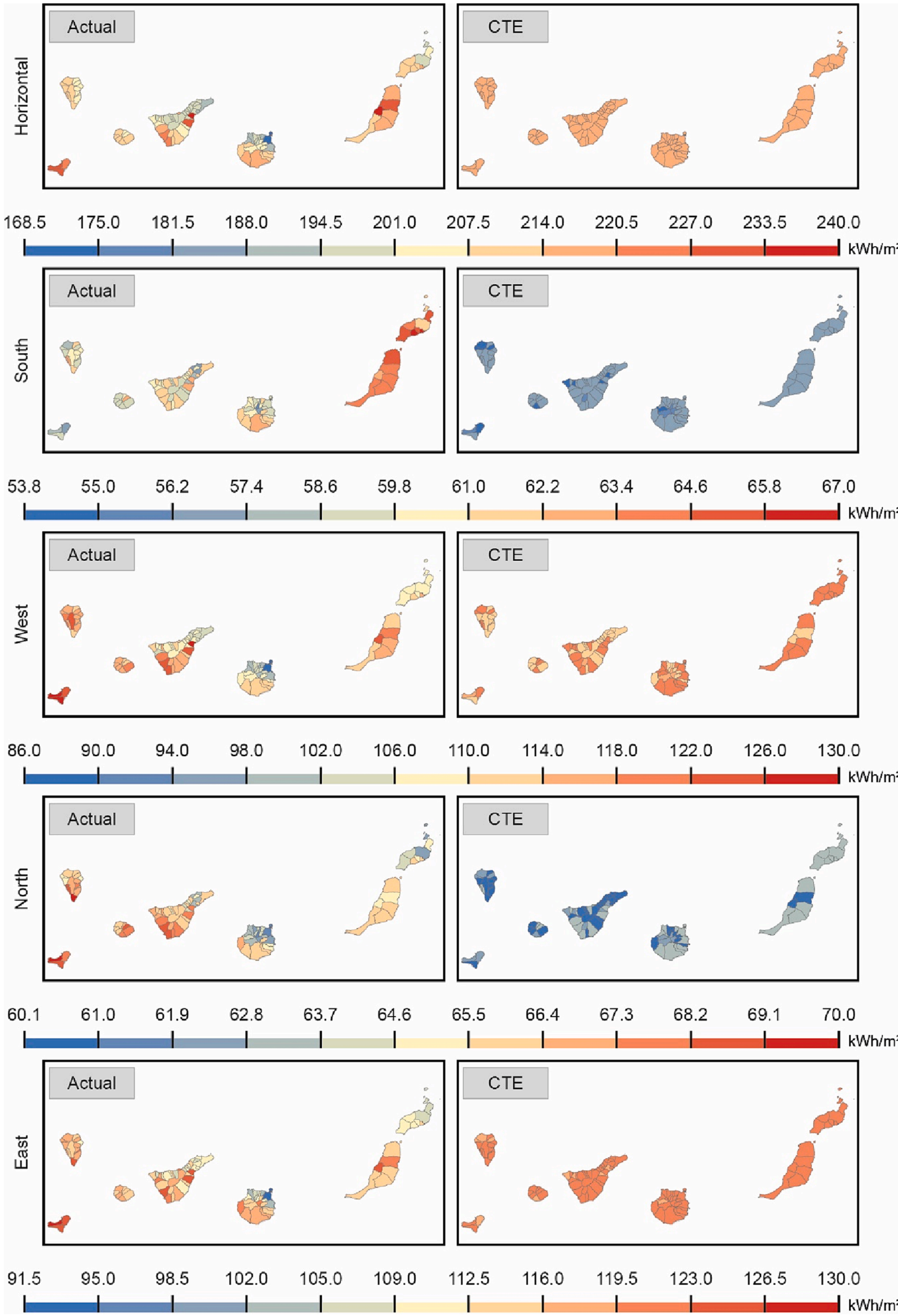

Fig. 6. Comparison between the actual values and the values of the Spanish Building Technical Code (CTE) of the accumulated solar irradiation in July (the Canary Islands). The results are shown for façades (south, north, east and west orientations) and roofs (horizontal).

7 algorithms. The analysis was performed by varying the number of clusters and with various classifications for the winter and summer months. The latter was done due to the differences in the results of solar irradiation by orientation between both seasons. Furthermore, the analysis allowed to identify the algorithm with lower deviations between the actual values of each municipality and the centroids of the new clusters. In other words, the approach with a more appropriate error distribution. As it is a simplification procedure of the number of zones of the country, there are always deviations. However, effective clusters could reduce the deviations of solar irradiation as much as possible. Fig. 8 shows the deviation distributions obtained by the algorithms. Except the clusters with a single algorithm, most of them led to

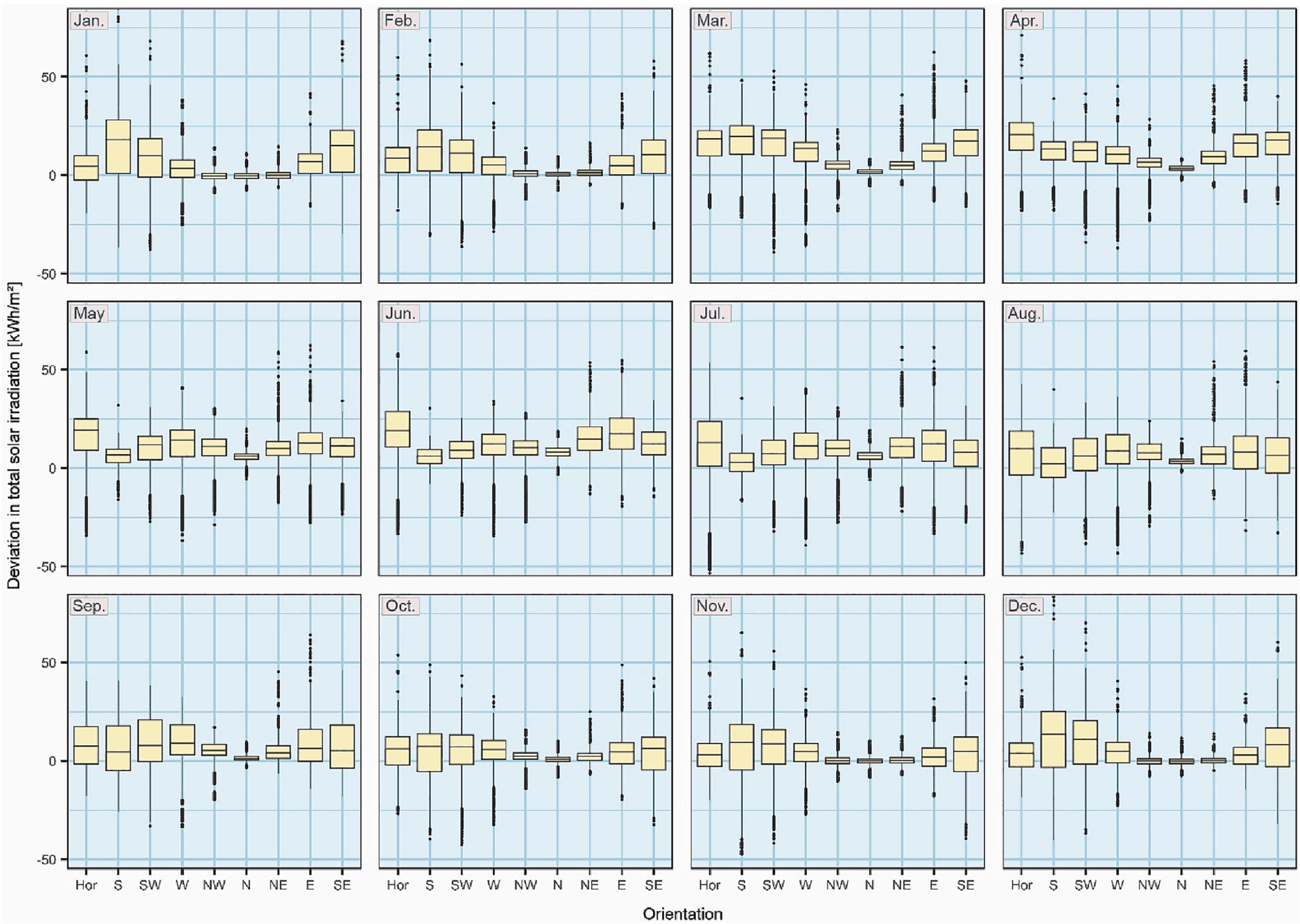

Fig. 7. Deviation of the accumulated solar irradiation values of the Spanish Building Technical Code (CTE) in comparison with the actual values. Results obtained throughout Spain (Iberian Peninsula and island territories).

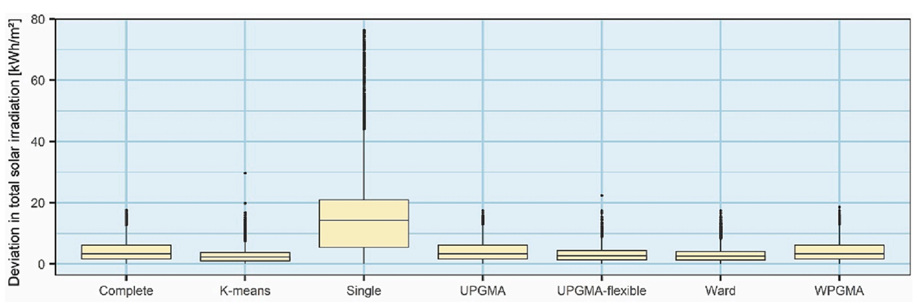

Fig. 8. Deviation of the accumulated solar irradiation values obtained by the various cluster algorithms.

low error distribution values. In this regard, the complete algorithm, UPGMA, and WPGMA obtained greater values in the quartiles in comparison with the remaining algorithms, with increases between 0.3 and 3.2 kWh/m^2. As for k-means, flexible UPGMA, and Ward method, the distribution results were almost identical, as well as the most adjusted to the actual values. However, the distributions of k-means algorithm had the lowest quartile deviation values: (i) k-means obtained a value of 0.9 kWh/m^2 in Q1, whereas Ward and UPGMA-flexible obtained values of 1.2 and 1.5 kWh/m^2, respectively; and (ii) the quartile deviation with k-means was 1 kWh/m^2, while UPGMA-flexible and Ward were 1.65 and 1.75 kWh/m^2, respectively. As observed, the k-means algorithm presented the lowest deviations in the distributions of municipalities, so it was used for the approach of the classifications. Nevertheless, it is worth stressing that algorithms of classification could also be used, such as Ward, since similar deviation values were achieved. This aspect could be crucial to extend this methodology to the climate and territorial context, as well as to the regulation as regards the influence of solar irradiation on building energy efficiency.

After finding k-means as the most appropriate algorithm in the classification approach to be used in Spain, the next step was the determination of the most appropriate number of clusters. For this purpose, two items were evaluated: (i) the municipality percentage with the greatest error in the approach of the CTE (i.e. the municipality percentage with greater deviation by using the approach of the CTE in comparison with the clusters obtained with the cluster analysis); and (ii) the average decrease of the differences with the cluster approach in comparison with that of the CTE. Fig. 9 summarises the results. As previously mentioned, different clusters took place in the cluster analysis for the winter and summer months, and various classifications were established for the Iberian Peninsula and the Canary Islands. As for the Iberian Peninsula, the progressive increase in the number of clusters improved the accuracy level of the values of monthly accumulated solar irradiation. The use of a low number of clusters (e.g. four clusters) obtained municipality percentages with greater error between 66.5 and 93.5% in the CTE approach. Hence, the use of a low number of clusters immediately implied that, in the most unfavourable case, 66.5% of municipalities had more representative values with the centroids of the cluster analysis. Nonetheless, the increase in the number of clusters led to municipality percentages with greater error in the approach of the CTE (between 72 and 96.3% with 20 clusters). These results did not individually provide an accurate vision of the effect of the cluster analysis on predictions. Thus, the average decrease of Fig. 9 and the point clouds represented in Fig. 10 show the effect of the variation of the number of clusters. Moreover, Fig. 10 reveals that the increase in the number of clusters implied that the distributions presented more points close to the axis of abscissas. This was an indication of the decrease in the deviations of monthly-accumulated solar irradiation. That decrease could be considered as low or null with a low number of clusters, whereas the use of a high number of clusters reduced the deviations with the cluster approach in comparison with the actual values, as well as allowed a greater approach to the diagonal of the graphs in the cases in which the municipalities presented greater deviation values. In this sense, the increase in the number of groups meant an average increase in the accuracy of the results of between 2.12 and 5.69% depending on the orientation. In the case of the results with many groups, it was detected how the results of the clusters were more representative than CTE in more than 75% of the municipalities, reaching results of up to 93% in some orientations. This aspect showed that the average decrease was 6.9% by each increase in the number of clusters. According to these results, the number of 20 clusters was the most appropriate to classify the regions in the Iberian Peninsula, as well as consistent with the number of municipalities and districts considered (8,822).

As for the Canary Islands, the lowest number of municipalities and districts of the region (126) implied that the number of clusters was lower (between 2 and 16). Fig. 9 shows the average results, and Fig. 11 shows the point clouds with the deviations of the cluster analysis in comparison with the deviations of the CTE. The increase in the number of clusters improved the accuracy of the values of accumulated solar irradiation. Along this line, the percentage of municipalities with greater error using the approach CTE showed an average increase of 1.7% in the summer months, whereas in the winter months most of the orientations obtained high values in the percentage of municipalities with greater error by using the approach of the CTE from the beginning. In other words, using a high number of clusters in the Canary Islands could be not required. According to the results, the use of 4 clusters in winter could be appropriate to obtained representative results in most part of the Canary Islands. As for the summer months, the increase in the number of clusters significantly reduced the existing deviations. In the range between 2 and 12 clusters there was a percentage decrease in the average error of up to 18.7%, whereas a decrease of up to 3.7% was obtained from 12 clusters onwards. Given both the low decrease from 12 clusters onwards and the number of municipalities of the region, a classification of 12 zones for the summer months was used.

These classification results for the Iberian Peninsula and the Canary Islands were used to assess the solar gains of the three case studies. Each case study obtained solar gains with and without the movable shading devices activated, using the procedure established by the CTE to calculate solar gains (based on ISO 52016-1). The results were obtained by using the actual values of accumulated solar irradiation of each municipality, as well as the centroids of the climate zones of the CTE and the centroids of the clusters obtained in the cluster analysis. Figs. 12 and 13 show the distributions. The results obtained with the centroids of the cluster analysis were very adjusted to the actual values. This was detected in the assessments conducted in both the Iberian Peninsula and the Canary Islands. In this regard, the values of solar gains obtained by the cluster approach presented errors between 0.9 and 3.7% in the Iberian Peninsula, and between 0.7and 2.2% in the Canary Islands. Errors significantly increased in the approach with the centroids of the climate zones of the CTE. Thus, errors ranged between 2.9 and 19.9% in the Canary Islands, and between 6.9 and 15.8% in the Iberian Peninsula. Likewise, it was detected that the standard deviation of the error obtained with the CTE results oscillated between 2.12 and 5.69%, while with the cluster analysis it oscillated between 0.45 and 0.94%. According to these results, the cluster analysis obtained more consistent clusters with more representative results. The procedure used by the CTE based on obtaining centroids of climate zones developed by using degree-days procedures presented many limitations. Its use could lead to assess the effect of solar gains on building energy performance inaccurately. In this regard, the CTE today establishes the control of solar gains in July: 2 kWh/m^2·monthly for private residential buildings, and 4 kWh/m^2·monthly for the remaining buildings. Given the deviation expected in the results (deviations of up to 19.9%), many case studies are

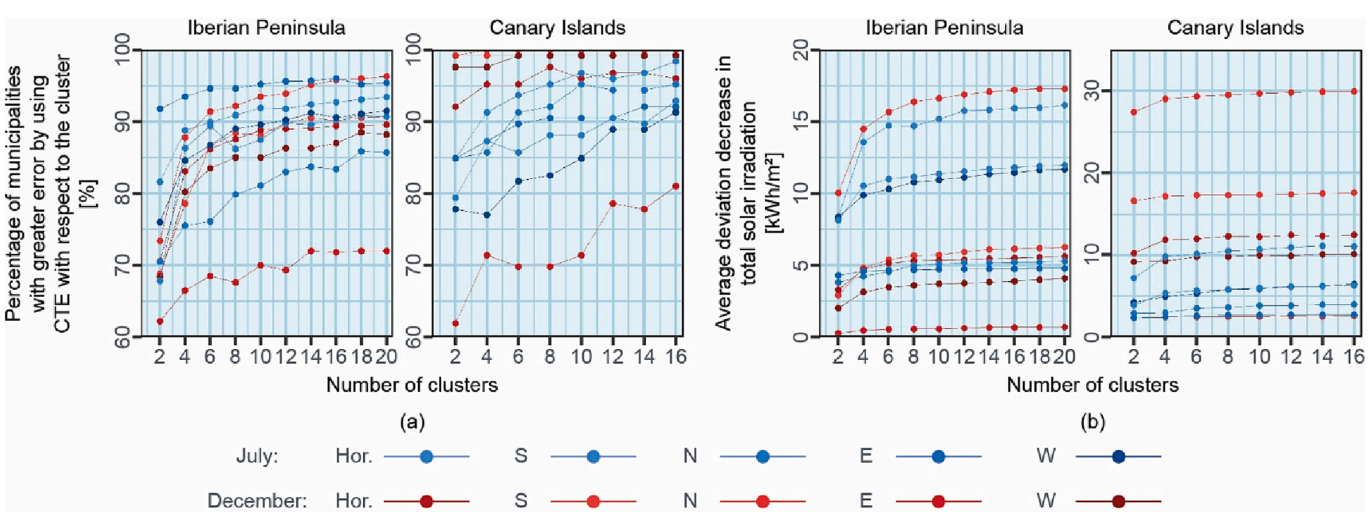

Fig. 9. Cluster performance analysis: (a) percentage of municipalities with greater error by using the approach of the Spanish Building Technical Code (CTE), and (b) deviation average decrease of the total solar irradiation values according to the number of clusters of k-means.

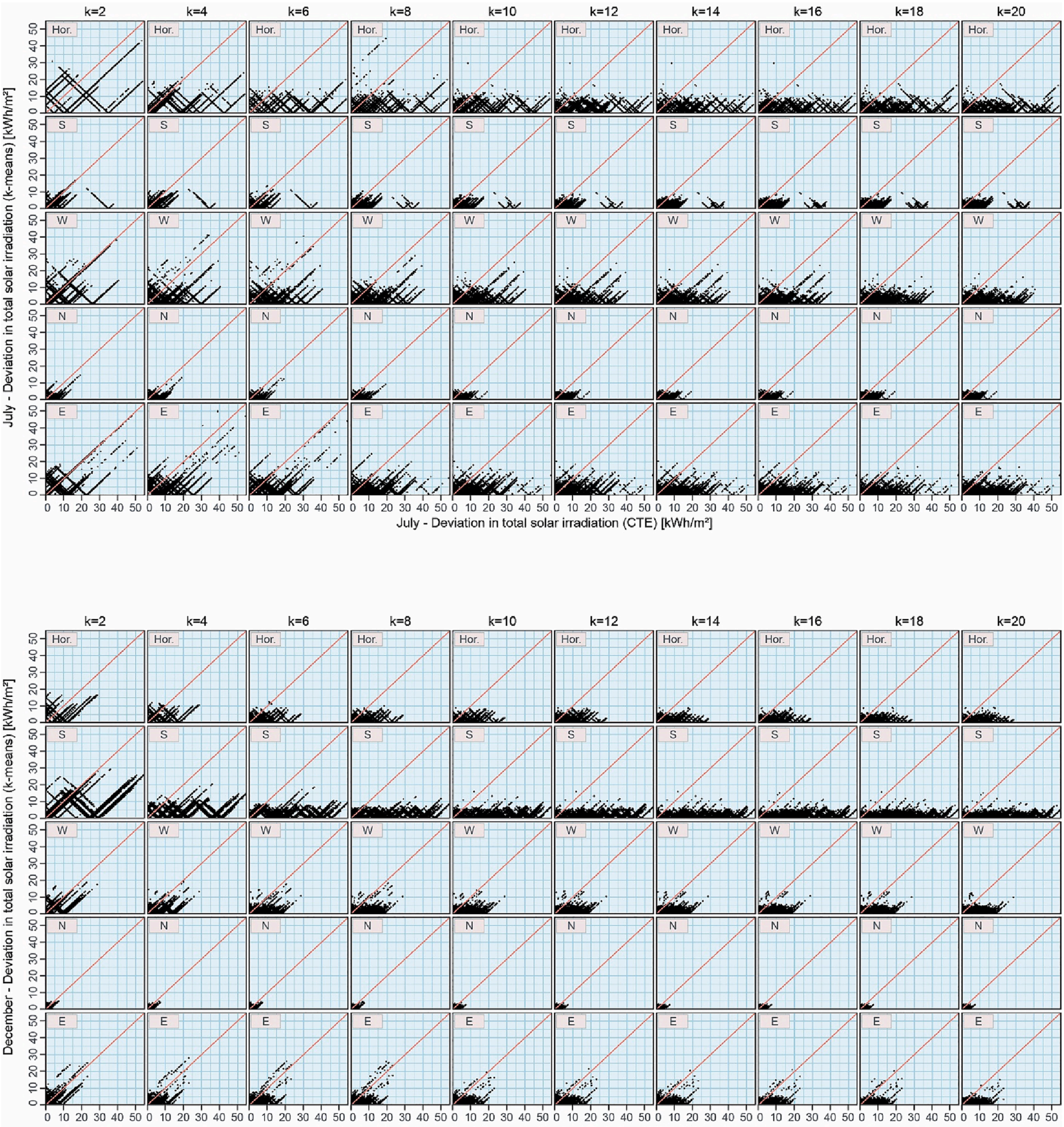

Fig. 10. Point cloud that compares the deviation of the solar irradiation values obtained by the cluster approach in comparison with the values obtained by the approach of the Spanish Building Technical Code (CTE). Results obtained in the locations of the Iberian Peninsula and the Balearic Islands.

likely to present actual results that do not meet these limit values. The use of a more adjusted criterion to establish solar irradiation zones and their centroids will allow the solar control of July (used by the CTE) to be analysed, as well as new control criteria for the winter months to be established. Given the characteristic of the regulation on energy efficiency in many countries [53], the results of this study are extrapolated to make a more appropriate control of solar gains.

4. Conclusions

Solar gains play a crucial role in building energy performance, particularly in zones with high levels, such as Spain. However, the recent modification of the national regulation has only promoted measures to control solar gains in the summer months. In fact, climate zones are categorized according to the heating and cooling degree-days to establish the values of monthly-accumulated solar irradiation by orientation.

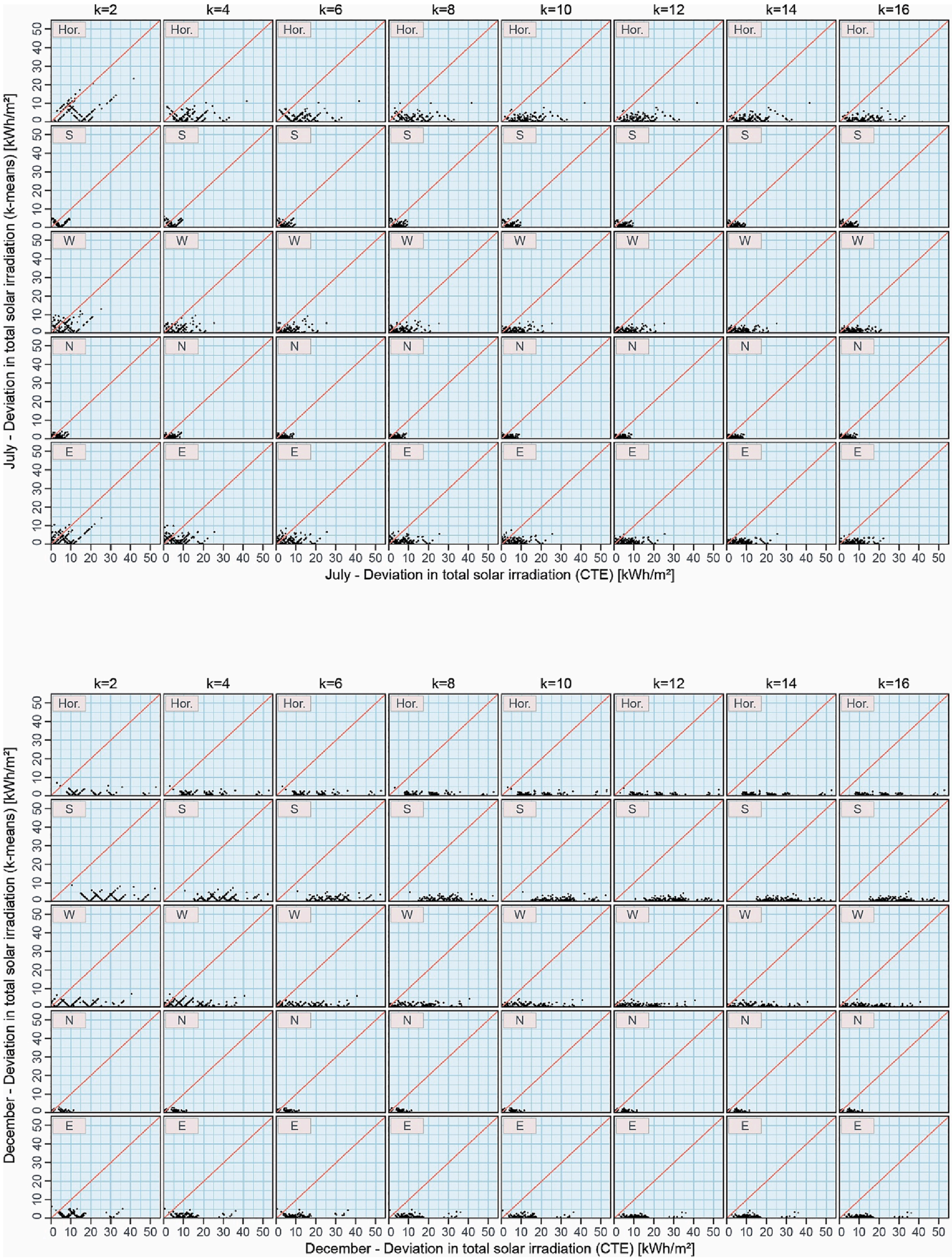

Fig. 11. Point cloud that compares the deviation of the solar irradiation values obtained by the cluster approach in comparison with the values obtained by the approach of the Spanish Building Technical Code (CTE). Results obtained in the locations of the Canary Islands.

Within this context, this research proposed an innovative approach for controlling solar gains based on clustering, analysing the actual data obtained for the 8,948 of municipalities and districts in Spain. The results presented significant deviations in comparison with the classification criterion of the Spanish Building Technical Code (CTE). Climate zones of the CTE use values of monthly-accumulated solar irradiation with deviations between −43.17 and 84.81 kWh/m^2 in comparison with the actual values. However, the differences mainly

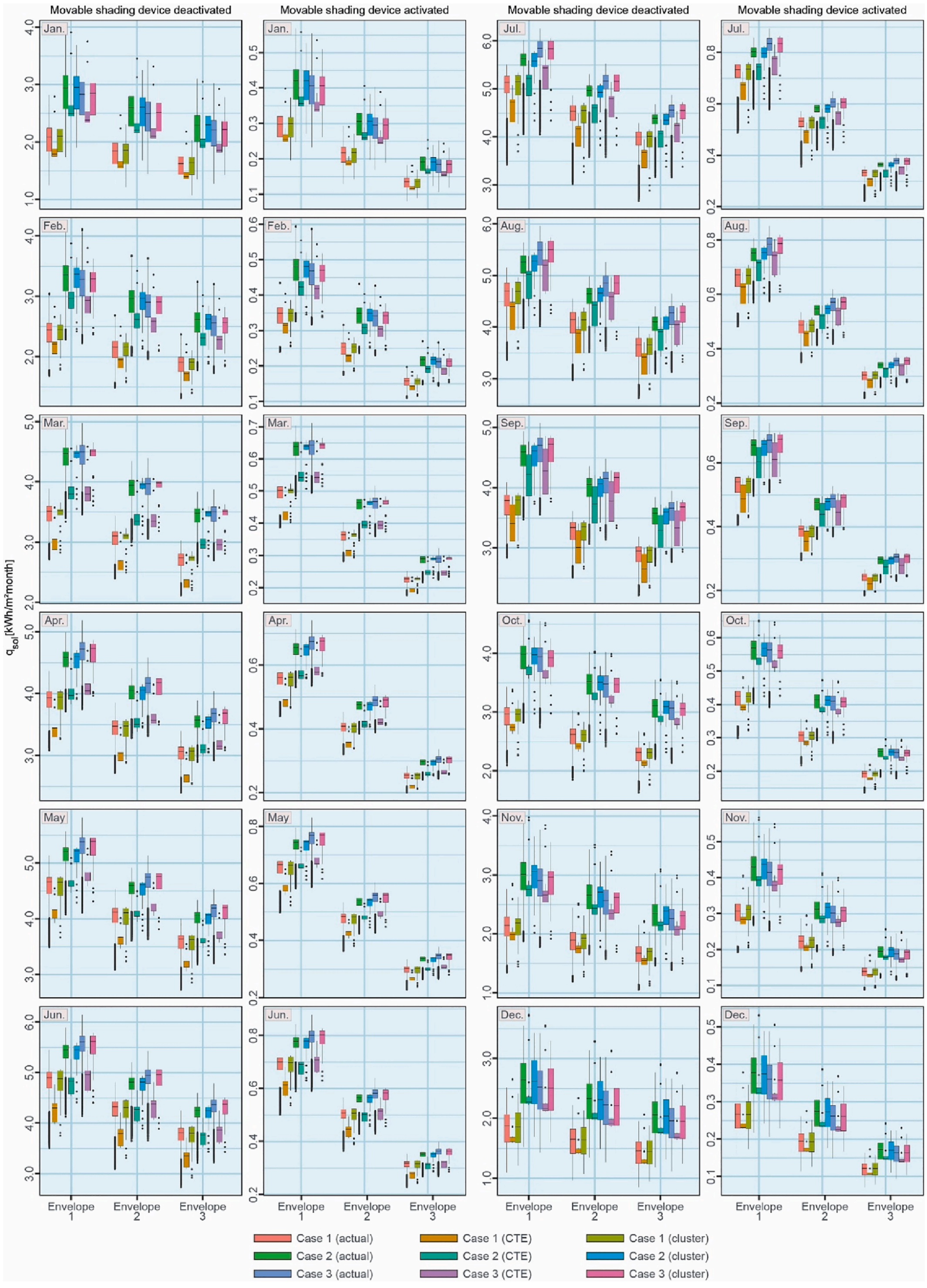

Fig. 12. Boxplots with the actual values of the solar gains with and without the solar systems activated, as well as of both the centroids of the Spanish Building Technical Code (CTE) and the centroids of the clusters obtained with k-means. Results obtained in the locations of the Iberian Peninsula and the Balearic Islands.

depended on location, and there were several trends for both the Iberian Peninsula and the Canary Islands. A crucial aspect was the marked difference in deviations, with greater values in the south, south-east, and south-west orientations in the winter months, as well as in the east and west orientations and in horizontal surface areas in the summer months.

Given the discrepancies mentioned above, the use of classification methodologies of the regions of the country to estimate the accumulated solar irradiation accurately could allow more appropriate. Most of the algorithms of classification computed in this study (k-means, Ward, UPGMA, flexible UPGMA, and WPGMA) were characterized by low deviations in comparison with the actual values. Nonetheless, the use of k-means was found to be the optimal approach. It should be noted that classifications of the winter and summer months should be divided due to be variation of the solar irradiation each month. The great effectiveness of the classifications was also reflected in the values of monthly solar gain with and without the shading devices activated in the three case studies located in the 8,948 locations. The deviations obtained by the centroids of the climate zones of the CTE, in comparison with the

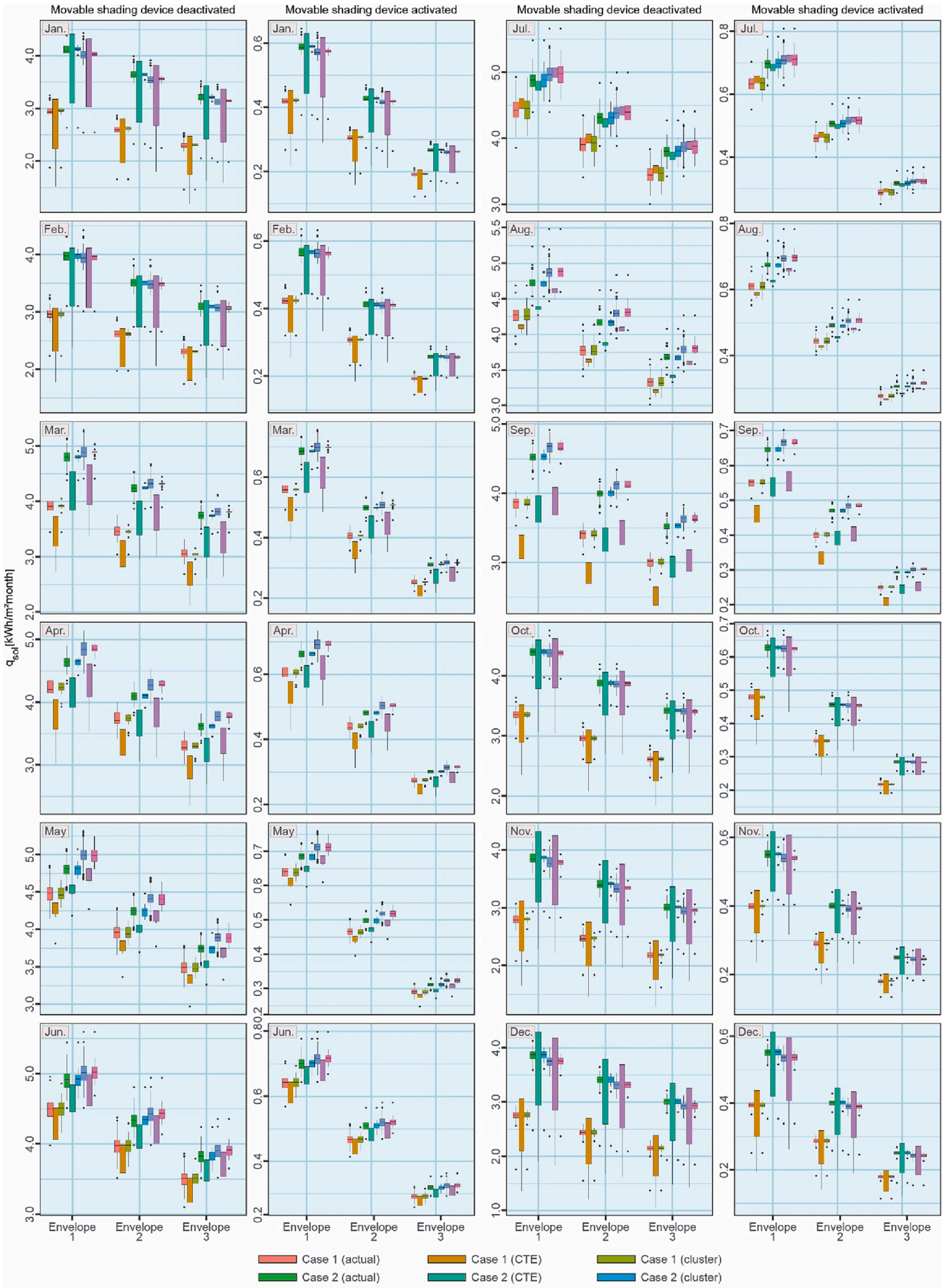

Fig. 13. Boxplots with the actual values of the solar gains with and without the solar systems activated, as well as of both the centroids of the Spanish Building Technical Code (CTE) and the centroids of the clusters obtained with k-means. Results obtained in the locations of the Canary Islands.

actual values, were between 6.9 and 15.8%, and between 0.7 and 3.7% in the clusters obtained by the cluster analysis. The results obtained with the cluster analysis therefore solved the limitations related to the classifications of the CTE.

To conclude, these results are of great interest to architects, engineers, and staff responsible for establishing the standards on energy efficiency. Simplified criteria for energy assessments is commonly used in many countries and make technicians' work easier. As for Spain, the major limitation of solar control values depends on the climate classification obtained by using degree-days. This climate classification procedure is common in many countries, from both the European Union (e.g. Italy and Portugal) and other continents (e.g. Chile) and is useful to classify climate by considering only the external air temperature. However, the results have shown that this calculation procedure is not appropriate to classify the accumulated solar irradiation. Thus, the implementation of the current methodology would be useful to obtain more accurate criteria for technicians and researchers of countries with a climate classification, especially to assess energy demand, since the goal is to give specific solar control criteria based on ISO 52016-1 and ISO 52022-1. In addition, the current findings highlighted the importance of solar control and outdoor conditions. In the state of the art, most studies have focused on the importance of windows, solar factor, and shading elements. Nevertheless, few studies have evaluated the characterization of outdoor irradiation conditions. If this characterization is limited (as in the case of standard construction methodologies), the results may have important deviations. The first limitation is related to the time span in which the clusters could be used in the current scenario. The climate change context could imply that municipalities change their clusters due to the evolution of climate throughout the 21st century. Further studies should focus on this aspect. Likewise, the limitations related to the use of solar irradiation maps to obtain geospatial data [54] were considered in this study. Further studies should also address the application of statistical models to estimate solar irradiation data by location, thus classifying climate more accurately. In this way, it is advisable to broaden the regional scope of the results. Although this study has only focused on Spain, the impact of solar radiation on the performance of buildings is present in all regions. In future work, the differences between each country's regulatory procedures and the actual data will need to be evaluated in-depth.

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.

Data availability

The authors do not have permission to share data.

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