Title:

Influence of adaptive energy saving techniques on office buildings located in cities of the Iberian Peninsula.

Highlights:

- Comparative study of standards: EN 15251:2007, EN 16798-1:2019, and ASHRAE 55-2017.
- A total of 780 dynamic simulations in 65 province capitals of the Iberian Peninsula.
- Climate analyses (current, 2050, and 2100) considering the scenario A2 of the IPCC.
- Use of adaptive setpoint temperatures to achieve energy saving.

Abstract:

The use of setpoint temperatures based on adaptive comfort algorithms is a method more and more used as an energy saving technique. Knowing the relationship between inhabitable rooms with their specific climate is crucial for users' climate adaptation, especially in a global warming context. This research analyses the influence of EN 15251:2007, EN 16798-1:2019, and ASHRAE 55-2017 standards on an office building located in 65 cities. The effects of climate change have been considered in the energy performance of current, 2050, and 2100 scenarios. Also, 780 dynamic simulations were performed so that a cluster analysis was carried out to determine the similarity relationships among the various zones. The results show that the model of the EN 16798-1:2019 standard was the option achieving a greater energy saving in current and future scenarios, and the use of energy was greatly reduced in those zones characterized by having a greater cooling energy consumption. Moreover, the differences of energy consumption between the adaptive models in the cities and years generated that the clusters presented differences among all cities, so such scenarios are required to be considered for future interventions. This research is the transition towards the goals proposed by the European Union for 2050.

Keywords:

Energy saving, adaptive setpoint temperatures, office building, cluster analysis, adaptive thermal comfort

1. Introduction

The natural environment is nowadays a continuous process of degradation. Constant natural disasters, environmental pollution, droughts, and extreme temperatures are leading to an environment more and more harmful to the survival in the planet. However, this is not a surprise. The possible combinations of future scenarios and their consequences for the life in the planet have been reflected by the Intergovernmental Panel on Climate Change (IPCC) in many studies (Intergovernmental Panel on Climate Change, 2007, 2014). The main reason of such degradation in the environment are greenhouse gas emissions (GHG). The production and energy consumption of non-renewable sources are among the major factors producing such emissions. Both the improvement of life quality in developed countries and the rapid economic growth in developing countries are generating a greater energy consumption (Allouhi et al., 2015). One of the main contributors to such energy consumption are the existing buildings. As for the European Union, buildings are responsible for 40% of the total energy consumption (European Commission, 2006; European Environment Agency, 2017), contributing with 36% of GHG emissions to the atmosphere (European Commission, 2002; European Union, 2010).

This situation has internationally led to a greater awareness of the need to establish measures to reduce GHG emissions. For this reason, the European Union has set a roadmap for moving to a low carbon economy for 2050 (European Commission, 2011). The objective is to achieve an economy without GHG emissions. As for the building sector, the objective is to reduce GHG emissions by 90% with respect to the levels in 1990 (European Commission, 2011). To do this, buildings should have a better energy performance. However, the main challenges for a more sustainable energy use in buildings are not only focused on a lower energy demand and the type of energy used, but also on how buildings are used (Allouhi et al., 2015). In recent years, various studies have emphasized the potential of energy saving due to the modification of the use of HVAC systems (which are the main consumption source in buildings (International Energy Agency, 2017)). The use of HVAC systems is modified by modifying in turn setpoint temperatures, thus generating important variations in this type of energy consumption (Ren & Chen, 2018). Most studies are focused on office buildings due to their high energy consumption: (i) Hoyt et al. (2014) used heating and cooling setpoint temperatures of 18.3 and 27.87 °C, respectively, in an office building located in San Francisco, Phoenix, Miami, Fresno, Duluth, Chicago, and Baltimore. By using such new setpoint temperatures, a saving between 32 and 73% was achieved in the building energy consumption with respect to its normal performance; (ii) in a similar study conducted by Parry et al. (2007), cooling setpoint temperatures were increased between 2 and 4 ºC in an office building in Zurich, thus significantly reducing the annual energy consumption; (iii) Wan et al. (2011) analysed the reduction of the energy consumption in office buildings in Hong Kong by modifying the setpoint temperatures in future climate change scenarios. The use of cooling setpoint temperatures greater than 25.5 °C significantly decreased the energy consumption in the different scenarios; and (iv) Spyropoulos and Balaras (2011) established setpoint temperatures of 26

°C for cooling, and of 20 °C for heating in Greek bank branches. The results reduced the energy consumption of HVAC systems by 45%.

These research works, however, used fixed setpoint temperatures which did not depend on the possible oscillations of the external temperature. The possibility of using other configurations achieving a greater energy saving was not therefore considered (Sánchez-García, Rubio-Bellido, del Río, & Pérez-Fargallo, 2019). The use of adaptive thermal comfort models constitutes an opportunity to obtain variations in setpoint temperatures, thus reducing the energy consumption and guaranteeing acceptable internal thermal comfort conditions. The consideration of such types of thermal models in setpoint temperatures (referred as adaptive setpoint temperatures in other studies) has been analysed in some studies: (i) Sánchez-Guevara Sánchez et al. (2017) analysed 3 buildings of social housing located in 3 Spanish climate zones. The authors used setpoint temperatures monthly varying by applying the adaptive thermal comfort model of the ASHRAE 55-2017 standard (American Society of Heating Refrigerating and Air Conditioning Engineers (ASHRAE), 2017), thus achieving an energy saving between 20 and 80% in buildings; (ii) Barbadilla-Martín et al. (2017) used as setpoint temperatures the neutral temperatures of a comfort model for mixed-mode buildings. Such model was designed for Seville. The energy consumptions obtained by using old setpoint and adaptive temperatures were compared (the old setpoint temperatures were 22.3 °C and 23.5 °C, whereas adaptive temperatures were 21.5 °C and 24 °C). Both energy savings of 27.5% in cooling and 11.4% in heating were obtained; (iii) in another study, different from the previous one, energy consumptions were quantified in office buildings by using the adaptive comfort limits of the EN 15251:2007 standard (European Committee for Standardization, 2007) as setpoint temperatures (Sánchez-García, Rubio-Bellido, del Río, et al., 2019). The results showed a reduction of the energy consumption between 36.7 and 59.5% with respect to the use of conventional setpoints; (iv) Sánchez-García et al. (2019) analysed also the application of adaptive setpoint temperatures according to the category III in the EN 15251:2007 standard (European Committee for Standardization, 2007) in a residential building located in 3 different climate zones, thus achieving a saving in the energy consumption between 10 and 46% with respect to the recommendations of the Spanish regulation on setpoint temperatures in this type of buildings; (v) in a recent study, Sánchez-García et al. (2019) analysed the energy saving achieved with the 3 categories of the EN 15251:2007 standard. The results showed that the energy saving was of 69.91% for the least restrictive category and of 31.34% for the category that presents a higher level of expectation; and (vi) Ge et al. (2018) studied the variation of setpoint temperatures in a university building. The use of setpoint temperatures of 26.8 °C for cooling and 19.9 °C for heating allow a decrease in cooling energy consumption to be achieved. So, these previous studies demonstrated the potential for the cooling energy savings obtained with adaptive models, thus reflecting the potential for the energy saving in climate change scenarios, which are characterized by an increase in the discomfort hours in summer (Escandón et al., 2019) and in the cooling energy demand (Osman & Sevinc, 2019). Moreover, the passive strategies together with the use of adaptive models allow the efficiency and sustainability of buildings to be guaranteed (Subhashini & Thirumaran, 2018).

The real possibilities of application of adaptive models have also been analysed in several studies: (i) Bienvenido-Huertas et al. (2019) analysed the possibilities of using weather stations to determine adaptive setpoint temperatures, with the result of estimating setpoint temperatures suitably even with weather stations located far from the building; (ii) Aparicio-Ruiz et al. (2018) applied an adaptive comfort algorithm to a real mixed-mode building and showed the real possibilities of applying such models by implementing them in the building automation system; and (iii) Aguilera et al. (2019) used a Personal Comfort Model (PCM) in a real case study by using fuzzy logic. This approach allowed the setpoint temperatures to be estimated in the HVAC system. In addition, the use of adaptive comfort models can imply that a building operates in free-running during many hours, thus exceeding 90% with acceptable building standards, even in cold climates (Pérez-Fargallo et al., 2018).

Existing studies therefore stress the potential of energy saving by using adaptive setpoint temperatures. However, the adaptive thermal comfort model implying a greater energy saving is not analysed. Also, most studies conduct analyses in a certain zone, and the possible relationships between various zones are not studied. For this reason, this study analyses the influence of using 3 different adaptive thermal comfort models on an office building located in 65 cities. Such cities are in the Iberian Peninsula and correspond to province capitals of Spain and Portugal. The Iberian Peninsula was selected because of its great climate variety (J.M. Pérez-Bella, Domínguez-Hernández, Cano-Suñén, Del Coz-Díaz, & Soria, 2017; José M. Pérez-Bella, Domínguez-Hernández, Cano-Suñén, Del Coz-Díaz, & Álvarez Rabanal, 2015). In addition, the energy performance of the case study was studied both in the current scenario and in an unfavourable climate change scenario for 2050 and 2100 (because of the effect of climate change on the energy efficiency of buildings (Kameni et al., 2019)). The cluster analysis was conducted to determine the similarity relationships among the various zones. The results of this study could be helpful to improve the energy efficiency of buildings and to mitigate the effect of climate change on thermal comfort and energy consumption. Moreover, results could be also helpful to develop energy policies by using adaptive models. This is due to the important role that governments have in the possibilities of applying adaptive strategies (Shooshtarian, Rajagopalan, & Sagoo, 2018).

This paper is structured by beginning with the methodology in Section 2, in which the case study analysed, the adaptive thermal comfort models used, the cities considered, and the criteria followed in the cluster analysis are described in detail. Section 3 discusses the results by distinguishing between the results obtained in the current scenario and those obtained in the future scenarios. Finally, the main conclusions are drawn in Section 4.

2. Methodology

2.1. Data collection and fieldwork

The case study is an office located on the fourth floor of an office building of fourteen floors (see Fig. 1) and with a surface area of 309 m^2. The building has 4 exposed façades facing north-west, north-east, south-east, and south-west. It is in Seville, but as indicated in section 1, it was located in different cities to analyse its energy performance.

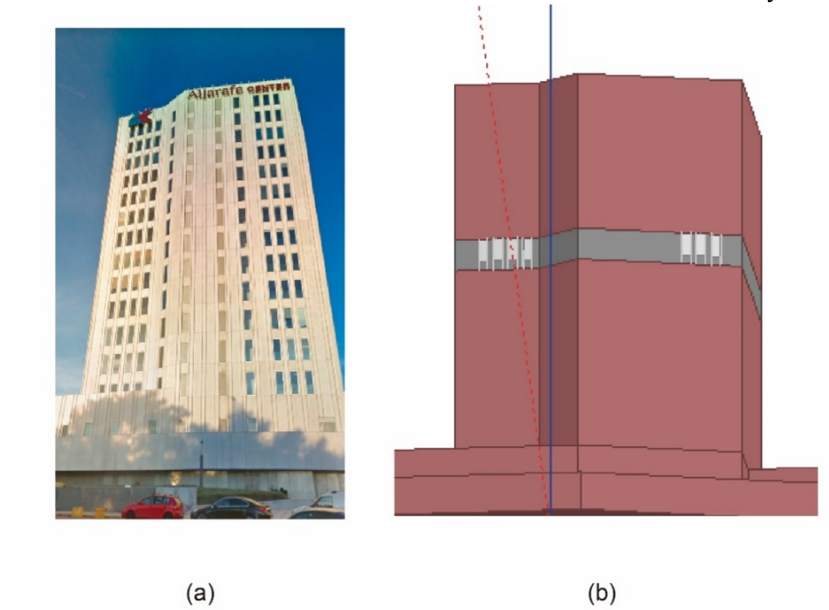

Fig. 1. Case study: (a) photograph of the office building; and (b) simulation model.

Data of the thermal properties of the envelope and the HVAC system have been collected (see Tables 1 and 2). The building envelope and constructive features meet the current energy and construction regulation and are typical in office buildings in this climate zone. The window-to-wall ratio was 0.28, and the glazed area that opened was 37 m^2, which represented 60% of the total glazed area. Moreover, occupants were interviewed, and temperatures were monitored. Both heating and cooling are provided by a Variable Refrigerant Flow (VRF) system, with an Energy Efficiency Ratio of 2.00 and a Coefficient of Performance of 2.10. Setpoint temperatures and operation schedules have been determined by interviewing the owner of the building, who indicated that the cooling and heating setpoint temperature were 25 °C and 23 °C, respectively, and were used both in open and closed offices. Moreover, systems were kept working continuously from 9 am to 7 pm on weekdays and were shut down on weekends. The owner also indicated that shutters were always kept open and windows were always kept closed. Occupancy schedules have been obtained through interviews: from 9 am to 2 pm and from 4 to 7 pm. Occupancy has been obtained by counting the occupants in each room. In this way, single closed offices and open offices have been considered separately. Thermal loads for each space have been determined by averaging similar spaces. Lighting and general equipment were only switched on during occupied periods. As weekends were not working days, there was no occupancy, so lighting and equipment were not used. Such data were used to design the simulation model in DesignBuilder.

Table 1. Thermal properties of the envelope.

Envelope	Layers	Thickness [mm]	U-value [W/(m^2K)]
Façade	Glassfibre reinforced concrete panels	100	0.76
	Air chamber	70	
	Mineral wool insulation	40	
	Plasterboard	13	
Window	Glazing: 6+12+6 mm1	-	2.82
	Aluminum frame2	-	4.72
Floor	Plasterboard suspended ceiling	15	1.38
	Enclosed air chamber	450	
	Concrete slab	300	
	Enclosed air chamber	150	
	Steel-clad particleboard raised floor	30	

Table 2. Loads in the case study.

Room	Loads [W/m^2]		
	Occupancy	Lighting	Equipment
Offices	6.2	12.1	4.6
Open workspaces	5.6	10.9	4.2

2.2. Validation of the simulation model

The simulation model was validated. For this purpose, the external temperature and internal temperature were monitored both in a non-occupied room without HVAC systems on the 14th floor and an occupied room with air-conditioning on the 4th floor (see Fig. 2). The external temperature probe was placed on the roof of the 2nd floor. The monitoring process was from 29 November 2016 to 20 June 2017 (see Fig. 3), and the interval of data acquisition was 1 hour (the dataset used was therefore composed by 14,616 instances). The outdoor temperature was measured by using a HOBO Pendant data logger 8K-UA-002-08 sensor, and the indoor temperature was measured with a HOBO U12-012 sensor. Sensors have been placed according to the ASHRAE 55-2017 standard. Probes were placed at a height of 1.1 m above the floor and positioned strategically to not receive external heat sources.

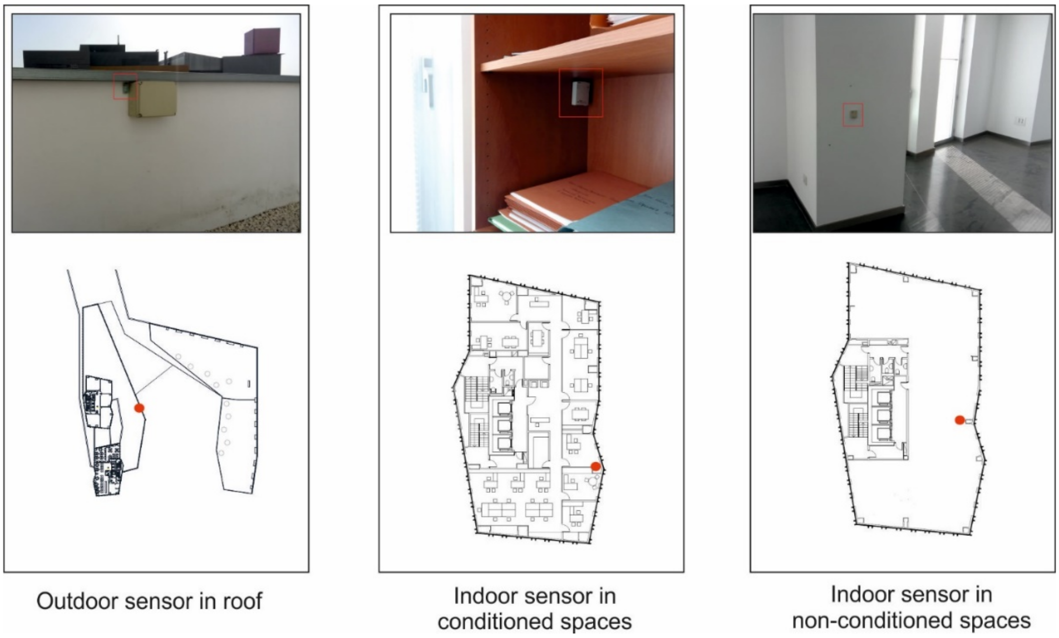

Fig. 2. Situation of the probes used in the validation process.

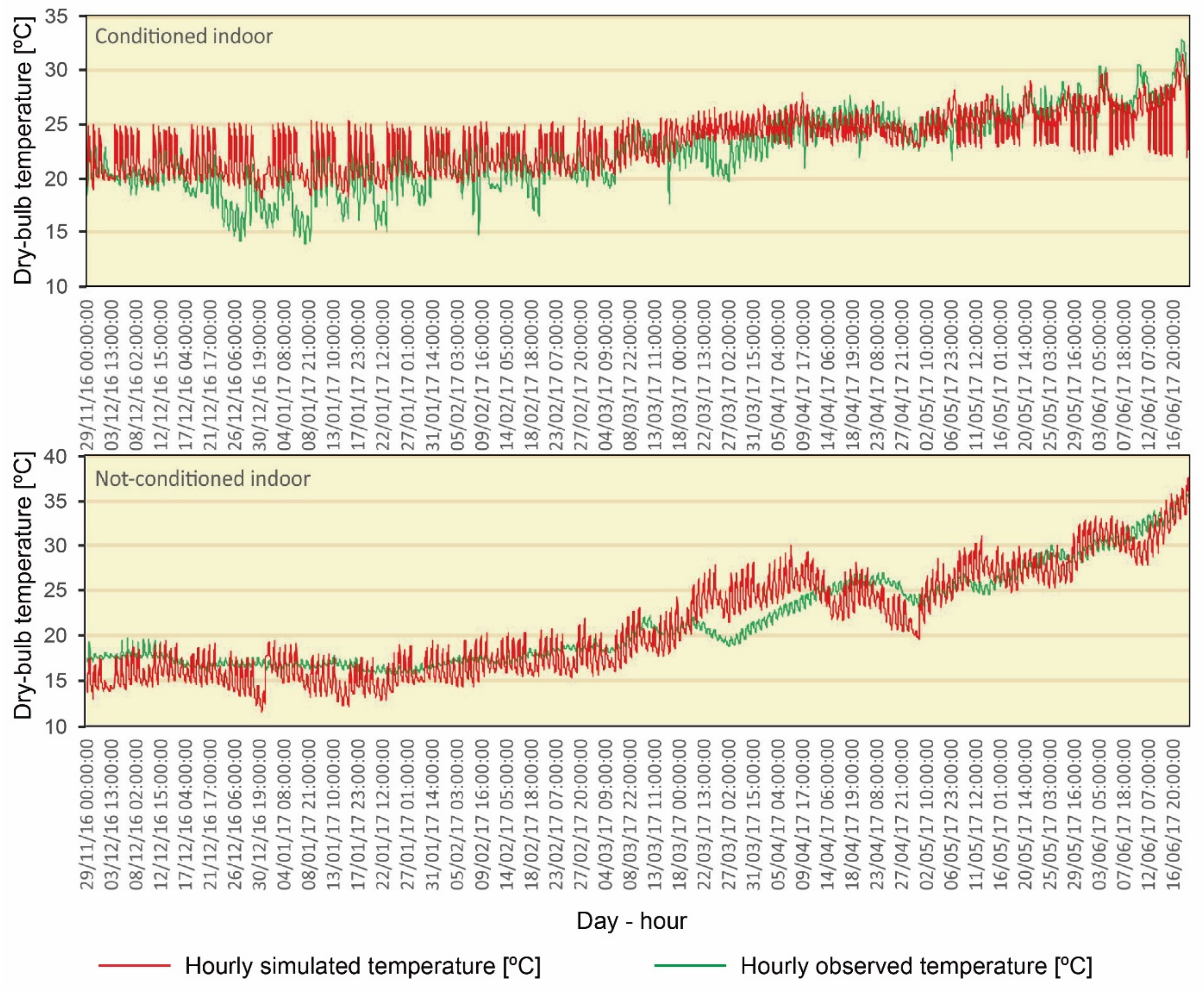

Fig. 3. Hourly simulated and measured temperature values along the whole monitoring process.

The building performance simulation model has been validated according to the ASHRAE Guideline 14-2014 (American National Standards Institute/American Society of Heating Refrigerating and Air-Conditioning Engineers (ANSI/ASHRAE), 2014) (see Table 3). For this purpose, the Mean Bias Error (MBE) (Eq. (1)) and the Coefficient of Variation of the Root Mean Square Error (CV(RMSE)) (Eq. (2)) were used as statistical parameters. The limit values set by the ASHRAE Guideline 14-2014 for hourly values are -10% ≤ MBE ≤ +10% and CV(RMSE) ≤30% (American National Standards Institute/American Society of Heating Refrigerating and Air-Conditioning Engineers (ANSI/ASHRAE), 2014). If the model fulfils these requirements, then it is calibrated.

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

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

Where y_i is the measured value, x_i is the simulated value, n is the number of measures, $\bar{y}$ is the average of measured values, and p is the number of adjustable model parameters (it is suggested to be zero for calibration purposes (Reddy, Maor, Jian, & Panjapornporn, 2006; Robertson, Polly, & Collis, 2013)).

Table 3. Results of the validation of the model

Variable	MBE [%]	CV(RMSE) [%]
Internal temperature (conditioned room)	-3.2%	8.7%
Internal temperature (not-conditioned room)	1.4%	9.0%

2.3. Thermal comfort models used for adaptive setpoint temperatures

As mentioned in Section 1, the objective of this study is to analyse the energy saving obtained by using adaptive setpoint temperatures. A total of 3 thermal comfort models are used. Such models are included in their respective standards: EN 15251:2007 (European Committee for Standardization, 2007), EN 16798-1:2019 (European Committee for Standardization, 2019), and ASHRAE 55-2017 (American Society of Heating Refrigerating and Air Conditioning Engineers (ASHRAE), 2017). The EN 15251:2007 standard was the first adaptive thermal comfort standard applicable to the whole Europe. Such standard sets 3 different categories of thermal comfort, giving recommendations according to the state of the building and the level of expectation of the occupant (e.g., category I should be used in spaces for weak and sensitive people with special requirements, category II should be used in new buildings, and category III in existing buildings). In each category, upper and lower limits are established for the operative temperature, and if it is outside such limits, the use of heating or cooling systems would be required. The higher the category, the higher the range of tolerance of comfort limits. Limits are calculated by first determining the running mean outdoor temperature (T_{rm}) (Eq. 3)) to then determine the limit values of each category (Eqs. (4-9)). To calculate the limits, T_{rm} is required to be within a value range depending on the type of limit: between 10 and 30 ºC for the upper limit, and between 15 and 30 ºC for the lower limit.

$$T_{rm} = (T_{ext,d-1} + 0.8T_{ext,d-2} + 0.6T_{ext,d-3} + 0.5T_{ext,d-4} + 0.4T_{ext,d-5} + 0.3T_{ext,d-6} + 0.2T_{ext,d-7})/3.8 \quad [ºC] \tag{3}$$

$$Upper\ limit\ (Category\ I) = 0.33 \cdot T_{rm} + 20.8 \quad [ºC] \quad (10 \leq T_{rm} \leq 30) \tag{4}$$

$$Lower\ limit\ (Category\ I) = 0.33 \cdot T_{rm} + 16.8 \quad [ºC] \quad (15 \leq T_{rm} \leq 30) \tag{5}$$

$$Upper\ limit\ (Category\ II) = 0.33 \cdot T_{rm} + 21.8 \quad [ºC] \quad (10 \leq T_{rm} \leq 30) \tag{6}$$

$$Lower\ limit\ (Category\ II) = 0.33 \cdot T_{rm} + 15.8 \quad [ºC] \quad (15 \leq T_{rm} \leq 30) \tag{7}$$

$$Upper\ limit\ (Category\ III) = 0.33 \cdot T_{rm} + 22.8 \quad [ºC] \quad (10 \leq T_{rm} \leq 30) \tag{8}$$

$$Lower\ limit\ (Category\ III) = 0.33 \cdot T_{rm} + 14.8 \quad [ºC] \quad (15 \leq T_{rm} \leq 30) \tag{9}$$

The EN 15251:2007 standard has been recently updated with the EN 16798-1:2019 standard (European Committee for Standardization, 2019), thus leading to two important changes with respect to the EN 15251:2007 standard: (i) T_{rm} should be within the range between 10 and 30 ºC for the lower limit; and (ii) correlations for the lower limit are modified, whereas they are the same for the upper limit. The new thermal comfort limits of the EN 16798-1:2019 standard are therefore as follows:

$$Upper\ limit\ (Category\ I) = 0.33 \cdot T_{rm} + 20.8 \quad [ºC] \quad (10 \leq T_{rm} \leq 30) \tag{10}$$
$$Lower\ limit\ (Category\ I) = 0.33 \cdot T_{rm} + 15.8 \quad [ºC] \quad (10 \leq T_{rm} \leq 30) \tag{11}$$
$$Upper\ limit\ (Category\ II) = 0.33 \cdot T_{rm} + 21.8 \quad [ºC] \quad (10 \leq T_{rm} \leq 30) \tag{12}$$
$$Lower\ limit\ (Category\ II) = 0.33 \cdot T_{rm} + 14.8 \quad [ºC] \quad (10 \leq T_{rm} \leq 30) \tag{13}$$
$$Upper\ limit\ (Category\ III) = 0.33 \cdot T_{rm} + 22.8 \quad [ºC] \quad (10 \leq T_{rm} \leq 30) \tag{14}$$
$$Lower\ limit\ (Category\ III) = 0.33 \cdot T_{rm} + 13.8 \quad [ºC] \quad (10 \leq T_{rm} \leq 30) \tag{15}$$

Finally, the ASHRAE 55-2017 standard is the adaptive thermal comfort model more applied internationally, and it establishes two types of limits according to the percentage of acceptability in the internal space: 80 and 90%. The correlations used to determine upper and lower limits have differences with respect to the limits used by the European standards. Likewise, the range in which T_{rm} should oscillate vary in the ASHRAE 55-2017 standard: T_{rm} should oscillate between 10 and 33.5 ºC for both the upper and lower limit.

$$Upper\ limit\ (80\%\ acceptability) = 0.31 \cdot \overline{t_{pma(out)}} + 21.3 \quad [ºC] \quad (10 \leq T_{rm} \leq 33.5) \tag{16}$$
$$Lower\ limit\ (80\%\ acceptability) = 0.31 \cdot \overline{t_{pma(out)}} + 14.3 \quad [ºC] \quad (10 \leq T_{rm} \leq 33.5) \tag{17}$$
$$Upper\ limit\ (90\%\ acceptability) = 0.31 \cdot \overline{t_{pma(out)}} + 20.3 \quad [ºC] \quad (10 \leq T_{rm} \leq 33.5) \tag{18}$$
$$Lower\ limit\ (90\%\ acceptability) = 0.31 \cdot \overline{t_{pma(out)}} + 15.3 \quad [ºC] \quad (10 \leq T_{rm} \leq 33.5) \tag{19}$$

For this study, the adaptive thermal comfort model with the greatest range of acceptability of the different standards was used: the thermal comfort model of the category III was used for the EN 15251:2007 and EN 16798-1:2019 standards, and the model with an acceptability of 80% for the ASHRAE 55-2017 standard. This criterion is also in accordance with two aspects: (i) the use of the category III, recommended for existing buildings, assessed the energy saving which could be obtained by modifying the use of the existing HVAC systems in buildings already built; and (ii) the category of acceptability of 80% was used according to the recommendations by the ASHRAE 55-2017 standard, which emphasizes the difficulty of obtaining an acceptability of 90% under actual conditions (American Society of Heating Refrigerating and Air Conditioning Engineers (ASHRAE), 2017). Although the EN 16798-1:2019 standard is an updating of the EN 15251:2007 standard, it is worth stressing that the adaptive thermal comfort model of the EN 15251:2007 standard was analysed because it has been widely used in previous research studies (Sánchez-García, Bienvenido-Huertas, et al., 2019; Sánchez-García, Rubio-Bellido, del Río, et al., 2019). Each limit was adapted to the operation schedule of the case study (see Table 4). The actual operation of the HVAC system of the building with a cooling setpoint temperature of 25 ºC and a heating setpoint temperature of 23 ºC was also considered (for this study, it was named as static model).

Table 4. Setpoint temperatures used in each model.

Model	Limit	Range	Setpoint temperature	
			9 am – 14 pm	16 pm – 19 pm
Static model	Upper limit	All	25	25
	Lower limit	All	23	23
EN 15251:2007	Upper limit	T_{rm}< 10 °C	26.1	26.1
		10 °C ≤ T_{rm}< 30 °C	Eq. (8)	Eq. (8)
		T_{rm}> 30 °C	32.7	32.7
	Lower limit	T_{rm}< 15 °C	19.75	19.75
		15 °C ≤ T_{rm}≤ 30 °C	Eq. (9)	Eq. (9)
		T_{rm}> 30 °C	24.7	24.7
EN 16798-1:2019	Upper limit	T_{rm}< 10 °C	26.1	26.1
		10 °C ≤ T_{rm}< 30 °C	Eq. (14)	Eq. (14)
		T_{rm}> 30 °C	32.7	32.7
	Lower limit	T_{rm}< 10 °C	17.1	17.1
		10 °C ≤ T_{rm}< 30 °C	Eq. (15)	Eq. (15)
		T_{rm}> 30 °C	23.7	23.7
ASHRAE 55-2017	Upper limit	T_{rm}< 10 °C	24.4	24.4
		10 °C ≤ T_{rm}< 33.5 °C	Eq. (16)	Eq. (16)
		T_{rm}> 33.5 °C	31.69	31.69
	Lower limit	T_{rm}< 10 °C	17.4	17.4
		10 °C ≤ T_{rm}< 33.5 °C	Eq. (17)	Eq. (17)
		T_{rm}> 33.5 °C	24.69	24.69

2.4. Cities and climate data

The main cities located in the Iberian Peninsula were analysed. The cities selected were the province capitals of Spain and Portugal: 18 cities in Portugal and 47 in Spain (see Fig. 4). Archipelagos of both countries were not included. Table 5 indicates the coordinates and altitudes of the cities. Their climate data were obtained with the METEONORM software (METEONORM, 2019). METEONORM is a software made up with 8,325 weather stations and determines climate hourly values in any location through interpolations. Both the EnergyPlus weather files required for simulations and daily external temperature values were achieved with METEONORM to calculate the limits of the adaptive models. The period of temperature to generate climate data was 2000-2009, and the period of radiation was 1991-2010. Such average years were considered in this study as the current scenario.

Climate data were also compiled for each city in the years 2050 and 2100. Such years were selected because the former is the date established by the European Union to achieve the objectives of a low-carbon economy, and the latter was chosen to analyse the performance of adaptive strategies at the end of the 21st century. The scenario A2 of the IPCC was selected because it is one of the most unfavourable scenarios (Nakićenović & Swart, 2000). It proposes a very heterogeneous world. The scenario A2 is characterized by both a continuous increase of population and economic developments focused on each region (Nakićenović & Swart, 2000). An increase between 2 and 5.4 ºC is planned in this scenario at the end of the 21st century with respect to the values at the end of the 20th century. Climate data of 2050 and 2100 were also obtained with METEONORM. METEONORM allows you to simulate 3 different climate change scenarios based on the IPCC report 2007 (these include A2). In each city, 4 different thermal models were analysed (that used in the building and 3 adaptive models) as well as 3 different climate scenarios (current, 2050, and 2100), so the results are based on 780 different simulations. The effect of future climate scenarios is reflected in the temperature and relative humidity (see Fig. 5). In the case of temperature, a progressive increase over the years is obtained, while relative humidity shows a more irregular trend with some downs and ups throughout the year.

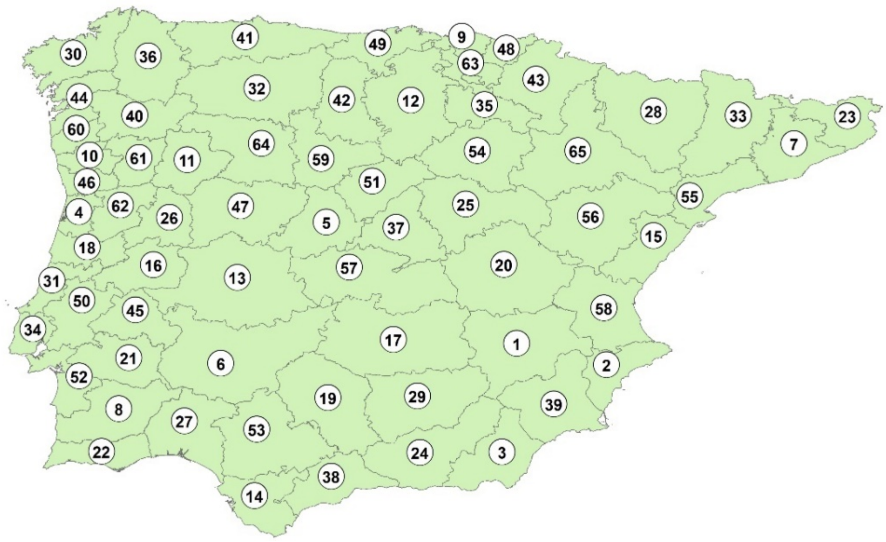

Fig. 4. Distribution of the provinces where cities are located.

Table 5. Coordinates and altitudes of cities.

City	Longitude	Latitude	Altitude	Point	City	Longitude	Latitude	Altitude	Point
Albacete	-1.855833	38.995556	681.00	1	Lisboa	-9.166670	38.716667	2.00	34
Alicante	-0.483056	38.345278	5.00	2	Logroño	-2.445556	42.470000	384.00	35
Almeria	-2.450000	36.833330	16.00	3	Lugo	-7.557222	43.011667	462.00	36
Aveiro	-8.655278	40.638889	25.00	4	Madrid	-3.691944	40.000000	657.00	37
Avila	-4.696222	40.654347	1,131.00	5	Malaga	-4.416667	36.716667	8.00	38
Badajoz	-6.975278	38.880278	182.00	6	Murcia	-1.130278	37.986111	42.00	39
Barcelona	2.176944	41.382500	13.00	7	Orense	-7.863333	42.336389	138.00	40
Beja	-7.883333	38.033330	243.00	8	Oviedo	-5.850278	43.362500	231.00	41
Bilbao	-2.953333	43.262220	6.00	9	Palencia	-4.533330	42.016667	749.00	42
Braga	-8.416667	41.533330	215.00	10	Pamplona	-1.650000	42.816667	450.00	43
Bragança	-6.750000	41.800000	700.00	11	Pontevedra	-8.647500	42.433611	16.00	44
Burgos	-3.699722	42.340833	859.00	12	Portalegre	-7.416667	39.316667	438.00	45
Caceres	-6.371111	39.473056	457.00	13	Porto	-8.610778	41.149472	104.00	46
Cadiz	-6.283333	36.516667	13.00	14	Salamanca	-5.663889	40.965000	798.00	47
Castellon	-0.050000	39.970000	27.00	15	San Sebastian	-1.980000	43.320000	7.00	48
Castelo Branco	-7.493139	39.823000	319.00	16	Santander	-3.800000	43.466667	8.00	49
Ciudad Real	-3.916667	38.983333	625.00	17	Santarem	-8.685000	39.236944	15.00	50
Coimbra	-8.407739	40.201272	43.00	18	Segovia	-4.116667	40.950000	1,002.00	51
Cordoba	-4.766667	37.883333	106.00	19	Setubal	-8.892611	38.524306	1.00	52
Cuenca	-2.135000	40.071667	997.00	20	Seville	-5.983330	37.383333	11.00	53
Evora	-7.907222	38.572500	295.00	21	Soria	-2.466667	41.766667	1,061.00	54
Faro	-7.933330	37.016667	10.00	22	Tarragona	1.245320	41.118680	69.00	55
Gerona	2.816667	41.983333	69.00	23	Teruel	-1.107222	40.343611	915.00	56
Granada	-3.600833	37.178056	684.00	24	Toledo	-4.033330	39.866667	516.00	57
Guadalajara	-3.166667	40.633333	685.00	25	Valencia	-0.375000	39.466667	16.00	58
Guarda	-7.268333	40.536389	1,056.00	26	Valladolid	-4.728561	41.651981	690.00	59
Huelva	-6.950000	37.250000	24.00	27	Viana Castelo	-8.833330	41.700000	2.00	60
Huesca	-0.408897	42.140100	483.00	28	Vila Real	-7.739850	41.300210	420.00	61
Jaen	-3.788889	37.769722	570.00	29	Viseu	-7.916667	40.666667	476.00	62
La Coruña	-8.383333	43.366667	21.00	30	Vitoria	-2.673056	42.846667	539.00	63
Leiria	-8.806944	39.743056	79.00	31	Zamora	-5.755556	41.498889	649.00	64
Leon	-5.566944	42.598889	837.00	32	Zaragoza	-0.883333	41.650000	208.00	65
Lerida	0.633330	41.616667	167.00	33					

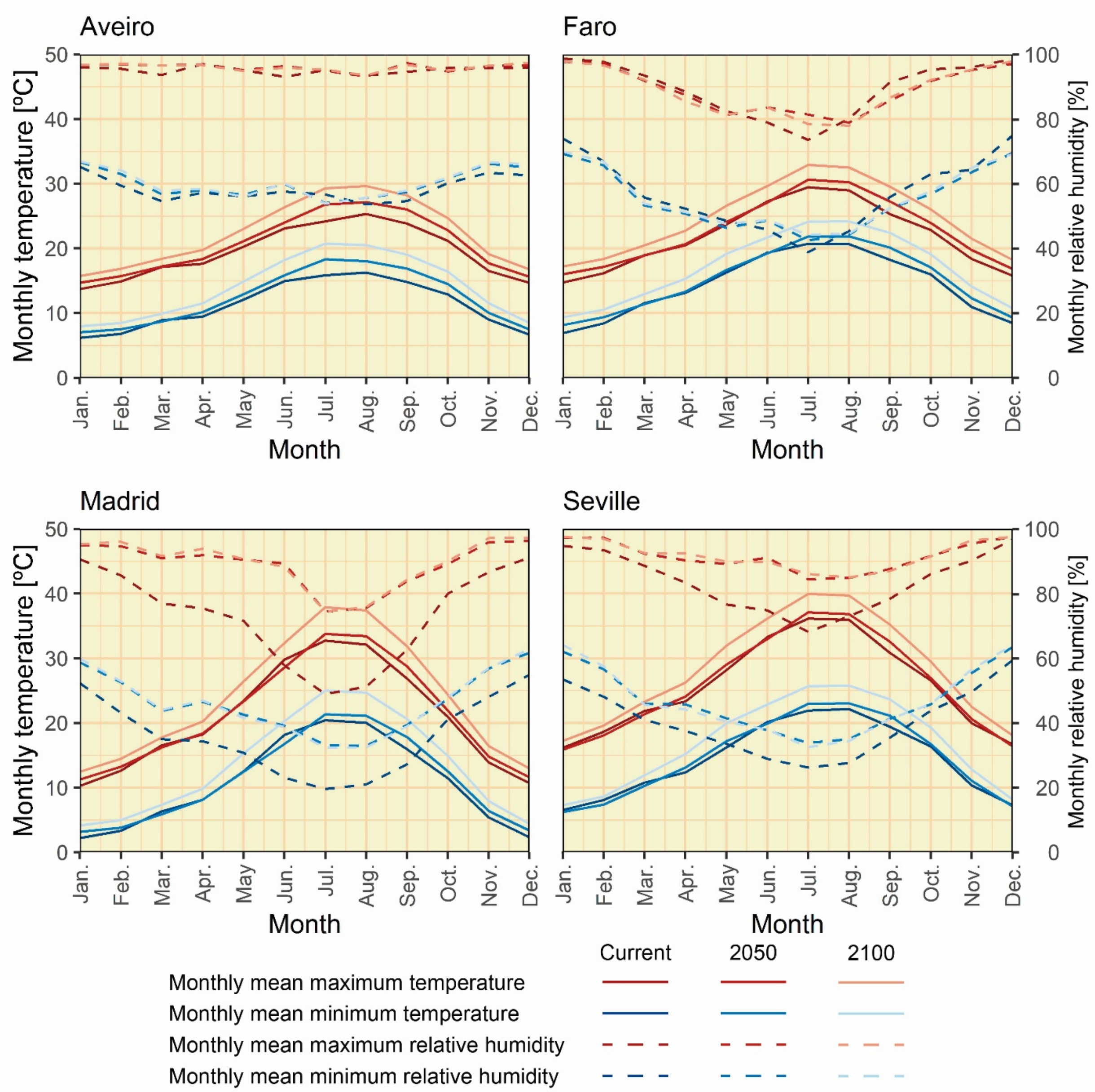

Fig. 5. Distribution of the provinces where cities are located.

2.5. Cluster analysis

As many cities were analysed, a cluster analysis was carried out to group the various zones in representative clusters. The cluster analysis is a non-supervised learning method which classifies data, giving different homogeneous clusters among them (Kaufman & Rousseeuw, 2009) (i.e., after carrying out the cluster analysis, the dataset is divided into k groups). A cluster analysis can be divided into two types of methodologies: (i) hierarchical methods, which can be distinguished between agglomerative (starting with a division of n groups with an instance in each, and then are grouped until achieving a division of a unique group of n instances) and divise (starting with a division of a unique group of n instances which is later divided until achieving a division of n groups of an instance); and (ii) non-hierarchical methods, whose starting point is the number k of groups expected to be achieved. Initially, such groups are made at random and then improved until achieving the optimal number k.

The average link method (Sokal & Michener, 1958), which belongs to the agglomerative hierarchical methods, is used in this study. Both clusters to be joined in each step were selected through the average distance between them (see Eq. (20)).

$$d_{average}(w_a,w_b) = \frac{1}{n_a \cdot n_b} \sum_{x_i \in w_a} \sum_{x_j \in w_b} d(x_i,x_j) \tag{20}$$

Where x_i and x_j are two individuals belonging to groups w_a and w_b, respectively; n_a and n_b are the number of individuals of groups w_a and w_b, respectively; and $d(x_i,x_j)$ is the distance between both individuals. In this analysis, the 65 cities considered in the study constituted the individuals of the cluster analysis. Two different cluster analyses were conducted according to the type of consumption, and the numbers of clusters ranging between 2 and 40 were analysed for each type of consumption to determine the most appropriate configuration, various cluster validity indexes were analysed: Ball-Hall index (Eq. (21)) (Ball & Hall, 1965), Baker-Hubert Gamma index (Eq. (22)) (Baker & Hubert, 1975), Calinski-Harabasz index (Eq. (23)) (Caliński & Harabasz, 1974), Davies-Bouldin index (Eq. (24)) (Davies & Bouldin, 1979), Dunn index (Eq. (25)) (Dunn, 1974), Generalized Dunn index (GDI) 51 (Eq. (26)) (Bezdek & Pal, 1998), and Tau index (Eq. (27)).

$$BHI = \frac{1}{K}\sum_{k=1}^{K}\frac{1}{n_k}\sum_{i \in I_k}\left\|M_i^{\{k\}} - G^{\{k\}}\right\|^2 \tag{21}$$

$$BHGI = \frac{s^+ - s^-}{s^+ + s^-} \tag{22}$$

$$CHI = \frac{N-K}{K-1}\cdot\frac{\sum_{k=1}^{K} n_k\left\|G^{\{k\}} - G\right\|^2}{\sum_{k=0}^{K}\sum_{i \in I_k}\left\|M_i^{\{k\}} - G^{\{k\}}\right\|^2} \tag{23}$$

$$DBI = \frac{1}{K}\sum_{k=1}^{K} M_k \tag{24}$$

$$DI = \frac{d_{min}}{d_{max}} \tag{25}$$

$$GDI51 = \frac{min_{k \neq k'}\delta_5(C_k, C_{k'})}{max_k\Delta_1(C_k)} \tag{26}$$

$$TI = \frac{s^+ - s^-}{\sqrt{N_B N_W\left(\frac{N_T(N_T-1)}{2}\right)}} \tag{27}$$

Where $G^{\{k\}}$ is the baricenter of the cluster; $M_i^{\{k\}}$ is the sum of the squared distances between instances; d_{min} is the minimum distance between individuals of different clusters; d_{max} is the maximum distance between individuals of a same cluster; s^+ is the number of concordant couples; s^- is the number of discordant couples; δ is a measure of the between-cluster distance; Δ is a measure of the within-cluster distance; and N_B, N_W and N_T are indicators of pair numbers.

3. Results and discussion

3.1. Current scenario

The analysis of the energy saving achieved in the case study by using adaptive setpoint temperatures was divided into the current scenario and climate change scenarios. Annex A includes the energy consumptions obtained in the cities by using different thermal models and in 3 time scenarios. Regarding the current scenario, existing differences in the energy consumption of the 3 adaptive thermal comfort models were assessed. For this purpose, both the heating and cooling energy consumption obtained in the 65 cities were assessed (see Fig. 6). Different results were obtained in the energy consumption by using different adaptive thermal comfort models. As for heating energy consumption, the use of setpoint temperatures according to the EN 15251:2007 standard implied a greater consumption than the other two models: the heating consumption in the EN 15251:2007 standard had an increase which ranged between 62.28 and 1023.58% with respect to the EN 16798-1:2019 standard, and between 49.87 and 920.29% with respect to the ASHRAE 55-2017 standard. It was also found that the use of the lower limit of the ASHRAE 55-2017 standard generated a greater heating consumption than in the EN 16798-1:2019 standard, with a percentage increase between 8.28 and 31.79% depending on the city analysed. As for cooling consumption, two aspects were highlighted: (i) as models of the EN 15251:2007 standard and the EN 16798-1:2019 standard has the same upper limit, the cooling energy consumption was the same; and (ii) the cooling energy consumption of the ASHRAE 55-2017 standard was higher than the others, with an increase which ranged between 30.32 and 187.36% depending on the zone analysed.

Models had therefore different performances, although the model of the EN 16798-1:2019 standard generally led to a lower energy consumption. A greater energy saving was achieved with respect to that obtained with the static model used by the office building in the reality (see Fig. 7). The energy saving achieved with the model of the EN 16798-1:2019 standard with respect to the static model ranged between 750.59 and 5027.36 kWh/year in heating, and between 2790.80 and 7698.96 kWh in cooling. Such values were different with respect to the value ranges of energy saving obtained by the other two models: (i) the EN 15251:2007 standard obtained a value range of heating energy saving between 899.82 and 2566.42 kWh/year depending on the city; and (ii) the ASHRAE 55-2017 standard obtained a value range of energy saving between 1135.96 and 4751.66 kWh/year, and between 1672.58 and 5718.95 kWh/year for heating and cooling, respectively, depending on the city. Thus, the energy saving both in heating and cooling was greater in the thermal model used by the EN 16798-1:2019 standard. This aspect was also found in the total energy saving in which the annual average value obtained with the EN 16798-1:2019 standard was greater in 17.60% and in 22.23% with respect to the models of the EN 15251:2007 standard and the ASHRAE 55-2017 standard, respectively. Consequently, two aspects were shown: (i) the greater energy saving obtained with the adaptive thermal comfort models developed for a certain region (EN 16798-1:2019) with respect to more generic models with a wider application (ASHRAE 55-2017); and (ii) the improvement in the energy saving obtained in the EN 16798-1:2019 standard by modifying its lower limit with respect to the previous European adaptive thermal comfort standard (i.e., the EN 15251:2007 standard).

Regarding the performance individually obtained in the various cities, the energy saving obtained in cooling consumption was greater than that obtained in heating consumption. In this sense, the average value of cooling energy saving was greater than that of heating, between 35 and 410% according to the adaptive model. Because of this, the energy saving was lower in those zones characterized by a lower cooling consumption with respect to the warmest zones: (i) Lugo, Oviedo, Santander, Guarda, and Vitoria were characterized by having a lower total energy saving. Such cities were also characterized by having a lower cooling energy consumption in the static model, with values ranging between 3481.44 and 5071.74 kWh/year; and (ii) Cordoba, Murcia, and Seville, characterized by a high cooling consumption in the static model (with values ranging between 12399.09 and 13189.00 kWh/year) obtained the highest total energy saving values, thus highlighting the climate influence on the saving achieved by using adaptive models.

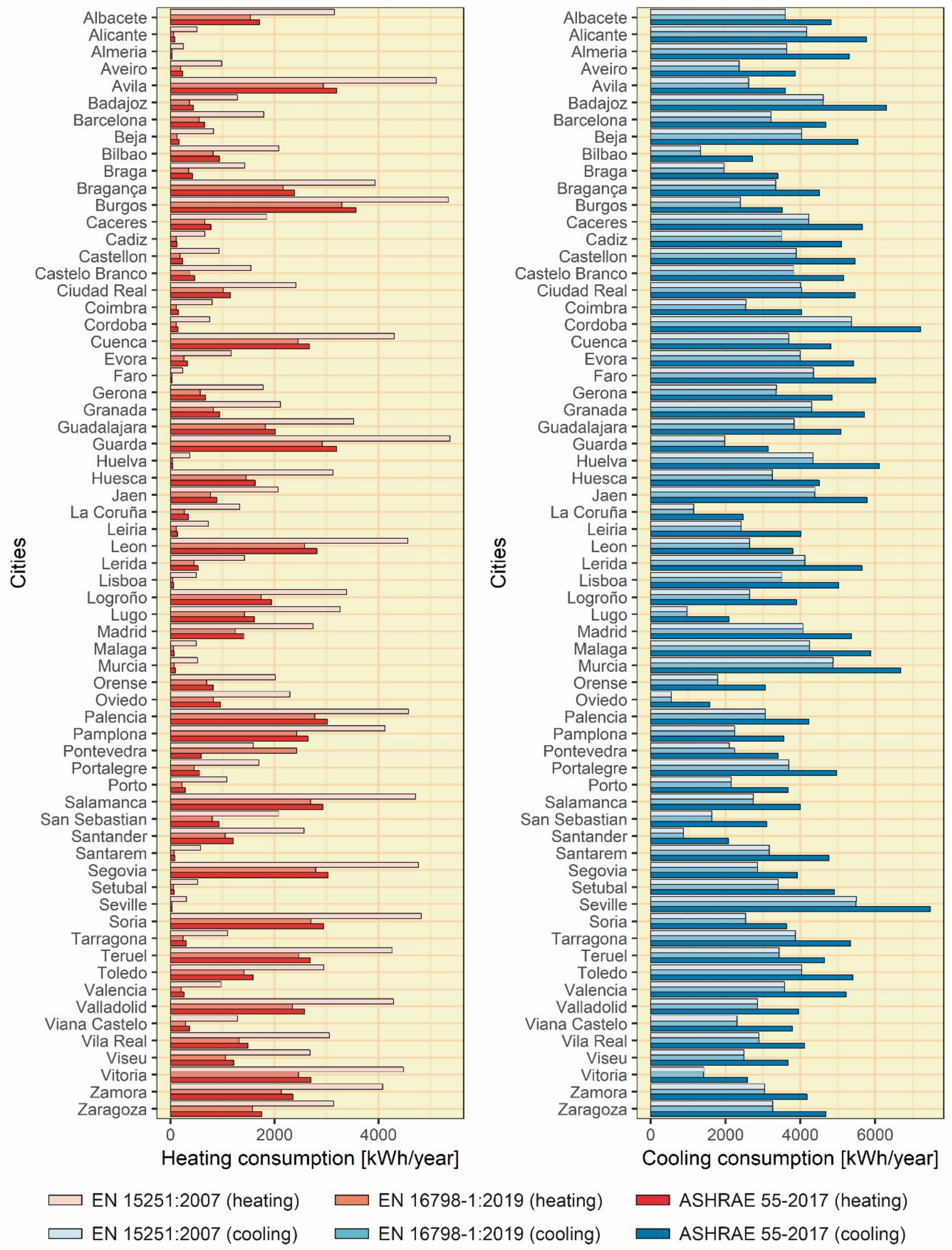

Fig. 6. Variations in heating and cooling energy consumption according to the adaptive thermal comfort model used.

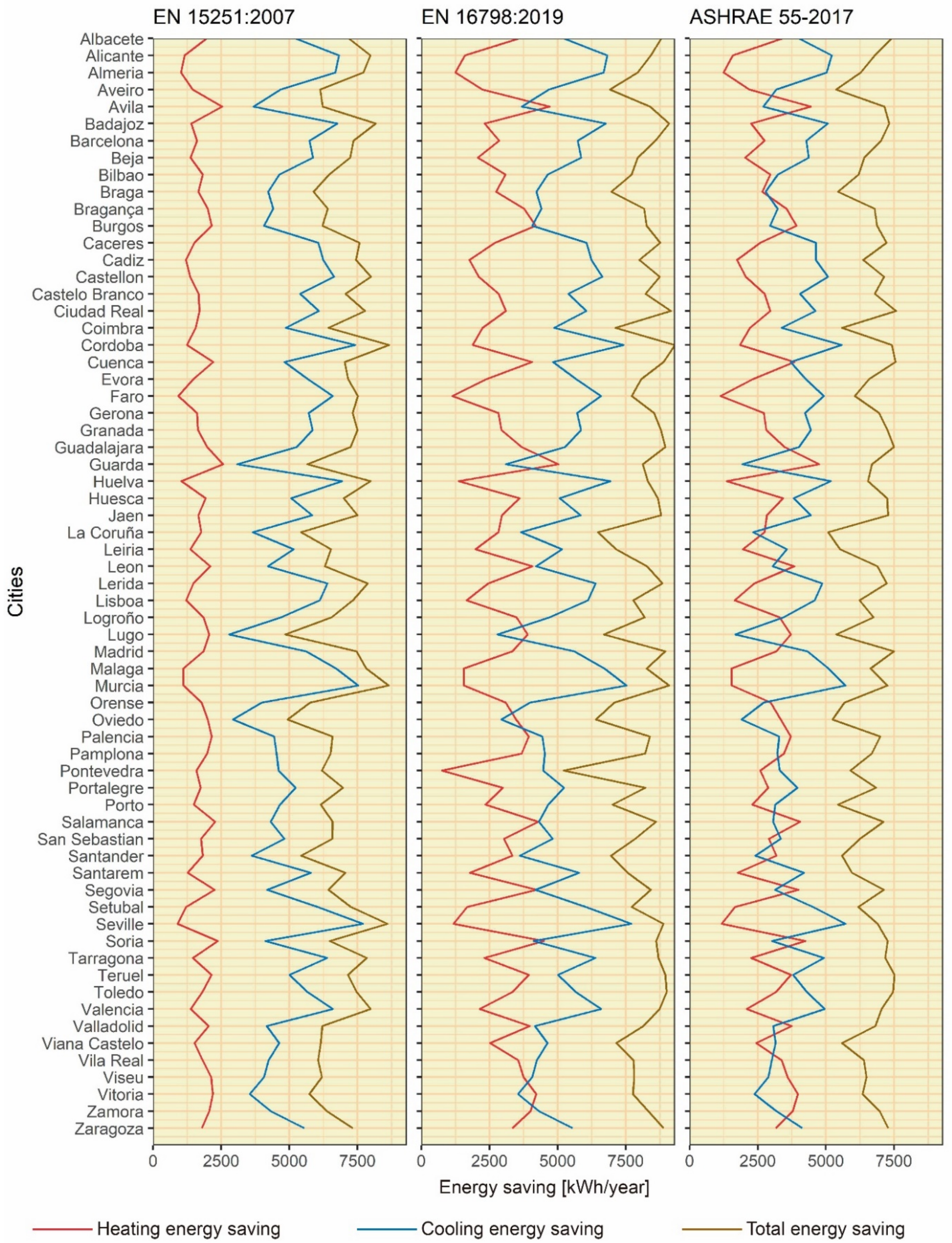

Fig. 7. Energy saving achieved by the adaptive models with respect to the static model.

There could therefore be similarity characteristics in the energy consumption of the adaptive models among various regions which establish clusters of the same type. For this reason, cluster analyses were carried out by using different adaptive models. As indicated in Section 2, the cluster analysis was independently carried out for annual heating and cooling consumptions. The various similarity zones were obtained by combining the different clusters obtained. Cluster indexes were used to validate the optimal number of clusters in the data used (see Figure 6). To ease the reading of results and to carry out a uniform comparison, Ball Hall, Calinski Harabasz, and Trace indexes were scaled in a range between 0 and 1. The number of clusters ranged between 2 and 40 for each type of consumption. By analysing the different indexes, the optimal number appearing most was determined: 9 for heating and 6 for cooling. This was a common aspect for the 3 adaptive thermal comfort models. The combination of 9 heating clusters with 6 cooling clusters generated a different number of zones in the models: 29 zones for the EN 15251:2007 standard, 27 zones for the EN 16798-1:2019 standard, and 26 zones for the ASHRAE 55-2017 standard. Such zones determined similarity patterns in the energy consumption obtained in the case study by modifying setpoint temperatures. Also, such variations generated differences in the cities grouped in the same zone (see

Fig. 8). In this sense, cities like Cadiz were differently grouped in the 3 adaptive models: (i) in the EN 15251:2007 standard, it was grouped with Valencia; (ii) in the EN 16798-1:2019 standard, Almeria, Lisboa, Setubal, Santarem, and Portalegre were included, apart from Valencia; and (iii) in the ASHRAE 55-2017 standard, Beja, Evora, Castellon, and Tarragona were also included. Such differences therefore show two aspects: (i) the climate influence on the clusters obtained in the adaptive thermal comfort models; and (ii) the lack of similarity in the zones obtained in the different adaptive models. As the model of the EN 16798-1:2019 standard obtained a greater energy saving, the classification carried out with such adaptive thermal comfort model can be considered as that with a greater potential of use. The use of adaptive thermal comfort strategies would therefore obtain similar energy savings in the cities grouped in the same zone. Also, the modification of the data used in the cluster analysis would obtain a more accurate classification. As a result, the use of a high number of different case studies, the increase of cities and the consideration of a unique adaptive thermal comfort model would imply a more detailed classification of the applications of adaptive models.

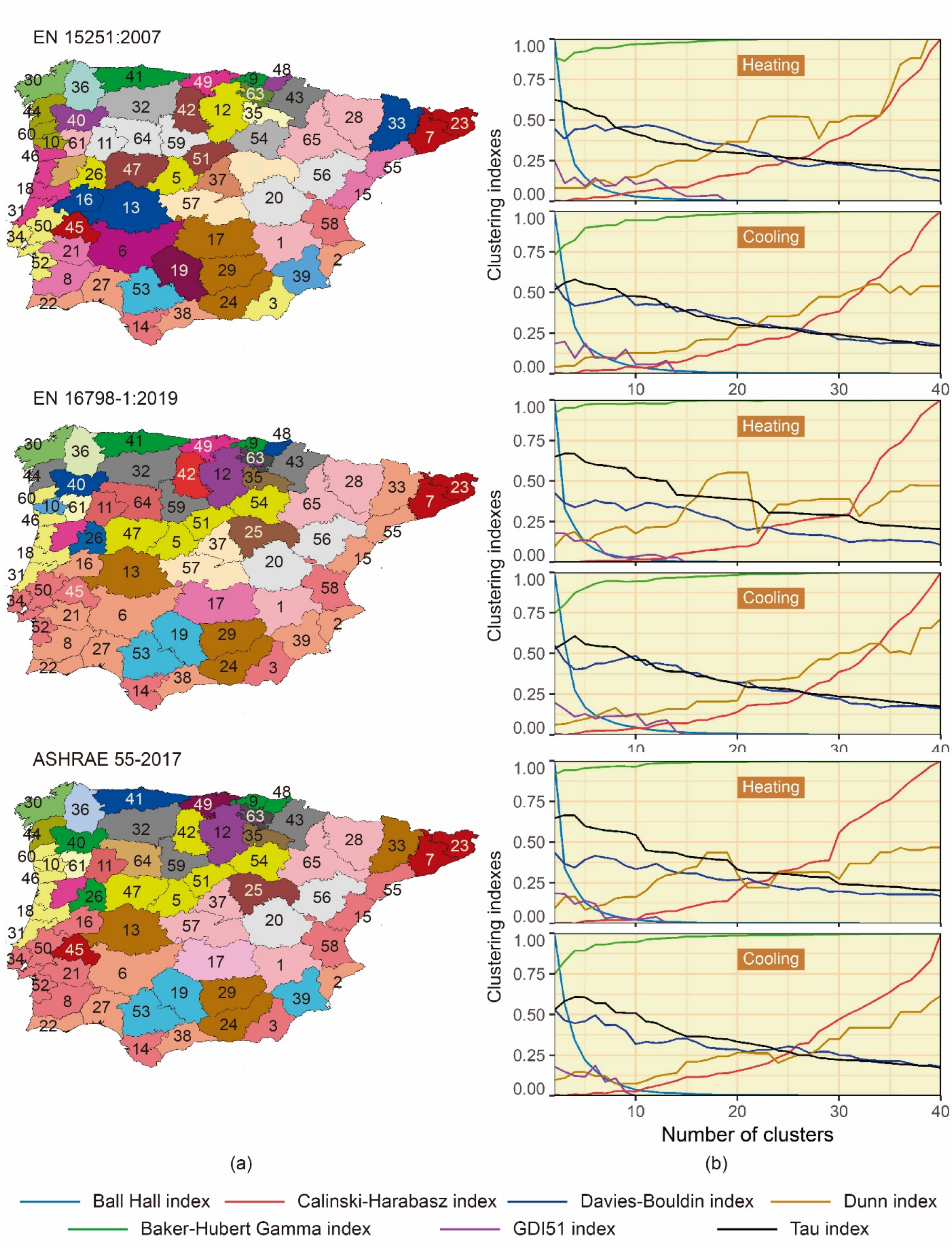

Fig. 8. Clusters obtained by the adaptive thermal comfort models: (a) zones obtained by each adaptive model in the cluster analysis. The chromatic codification among the various maps is not the same due to the different clusters carried out in each model. It provides the reader with the cities grouped in a same cluster; and (b) values of the cluster indexes.

3.2. Climate change scenario

After analysing the performance of the energy saving in the current scenario, it was analysed in future scenarios influenced by climate change. As indicated in Section 2, the years 2050 and 2100 were considered in the scenario A2 of the IPCC (Nakićenović & Swart, 2000). Firstly, existing differences among the total consumption values obtained by the models used for setpoint temperatures were analysed. Fig. 9 represents the violin plots of the distributions of the annual heating, cooling, and total consumption values. As explanatory note, violin plots are an evolution of box-plots which give information about the concentration of values through a kernel density curve (Hintze & Nelson, 1998). In future scenarios, similar tendencies to that obtained in the current scenario were found: (i) the consumption of the static model was greater than that obtained in adaptive models; and (ii) among the adaptive models, the EN 16798-1:2019 standard obtained the lowest energy consumption. This aspect is reflected in the greatest concentration of instances in the lowest energy consumption values. The variation of climate conditions in the 65 cities with the scenario A2 did not therefore modify the performance of adaptive models, with the EN 16798-1:2019 standard being the best approach to achieve a greater energy saving. It was found, however, that the use of adaptive setpoint temperatures presented different tendencies in the energy saving according to the type of consumption (see Fig. 10). In this sense, the heating energy saving of adaptive models with respect to the static model decreased in the future scenarios with respect to the current one, whereas the cooling saving increased: (i) the saving in heating consumption had an average decrease between 193.66 and 438.59 kWh/year, and between 481.24 and 960.20 kWh/year in 2050 and 2100, respectively. It was also found that the energy saving was lower with the model of the EN 15251:2007 standard than with the other adaptive models; and (ii) the saving in cooling consumption had an average increase oscillating between 705.79 and 894.25 kWh/year in 2050 and between 1896.53 and 2443.30 kWh/year in 2100. Fig. 9 shows that the greatest type of consumption in the static model in 2050 and 2100 was cooling, so the use of adaptive setpoint temperatures would guarantee a more sustainable use of office buildings in the cities of the Iberian Peninsula. In addition, although the saving in heating was lower in the future scenarios than in the current one, the decrease achieved with adaptive setpoint temperatures ensures a more sustainable use of the building.

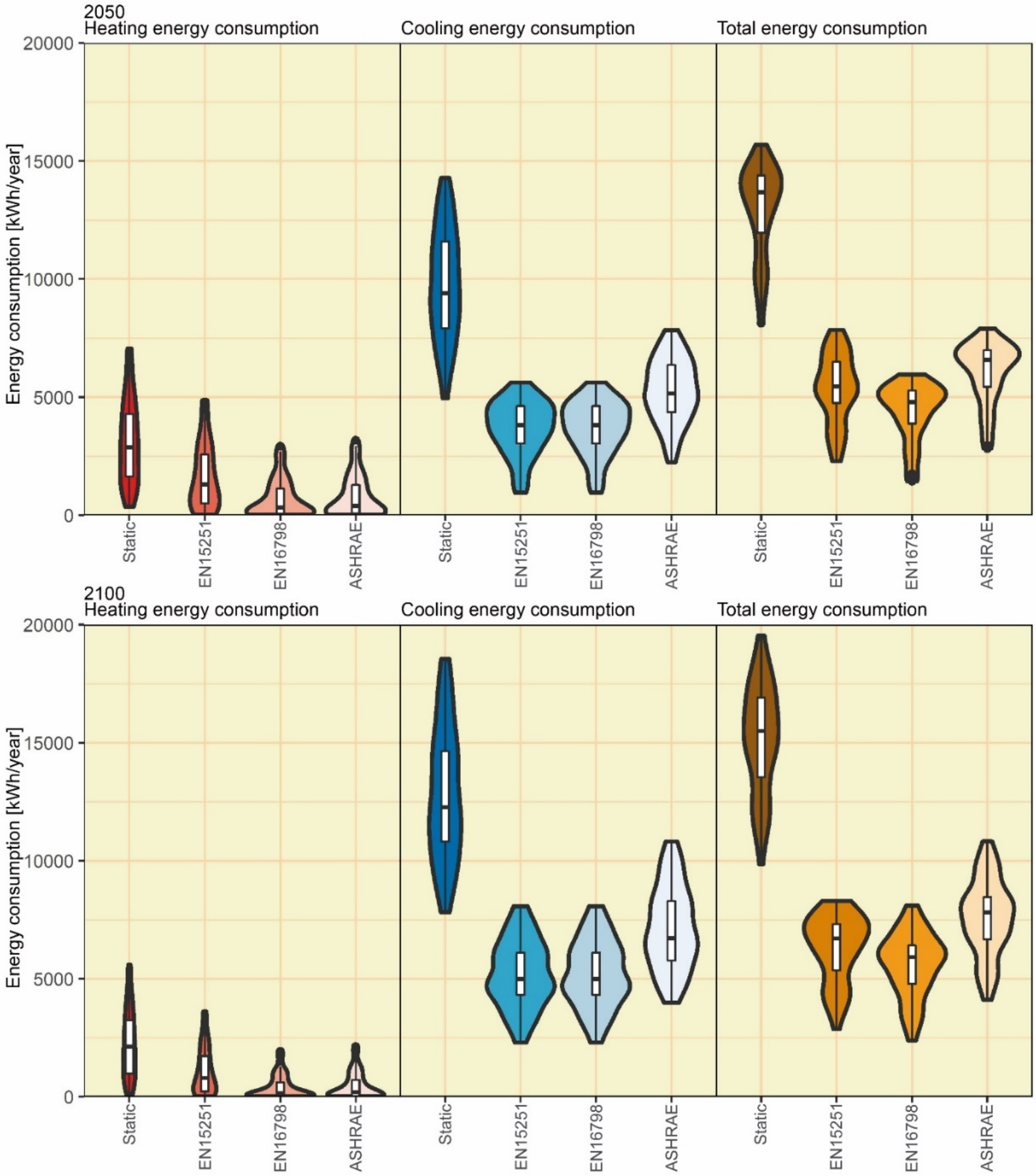

Fig. 9. Violin plots with energy consumption values in the future scenarios obtained by the different comfort model used for setpoint temperatures. A box plot of the distribution of energy consumption values is also included.

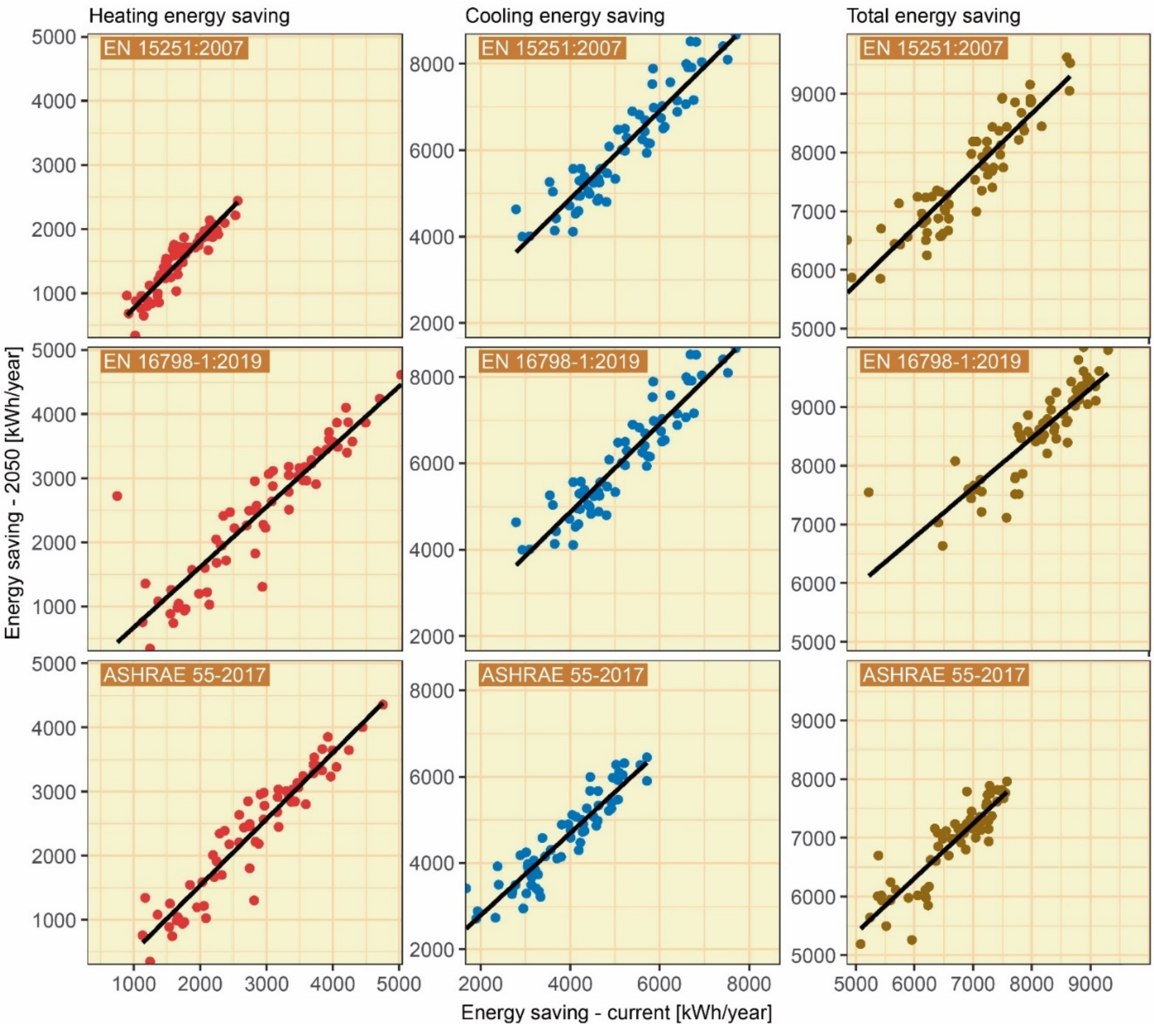

Fig. 10. Point clouds between the energy saving achieved in the current scenario and the energy saving achieved in the year 2050 for the adaptive thermal comfort models with respect to the static model.

Finally, the influence of the climate variations of the scenario A2 was analysed in the clusters of the city. The analysis was conducted by considering the same number of clusters for both types of consumption obtained in the current scenario: 9 for heating and 6 for cooling. As Fig. 11 shows, the variations of the scenario A2 generated different clusters among the cities. Such differences were found between the same adaptive comfort model in the different years and between the adaptive models, thus showing the changing performance presented by using adaptive setpoint temperatures in Spanish cities. Also, similarities can be presented with different cities throughout the years. It is worth stressing, however, that similarities are usually logic and have a pattern (e.g., Cordoba and Seville are usually grouped within the same zone in most classifications). Anyway, the increase of the number of case studies and the consideration of a larger number of cities would imply a more accurate classification of the application potential of ECMs based on adaptive setpoint temperatures.

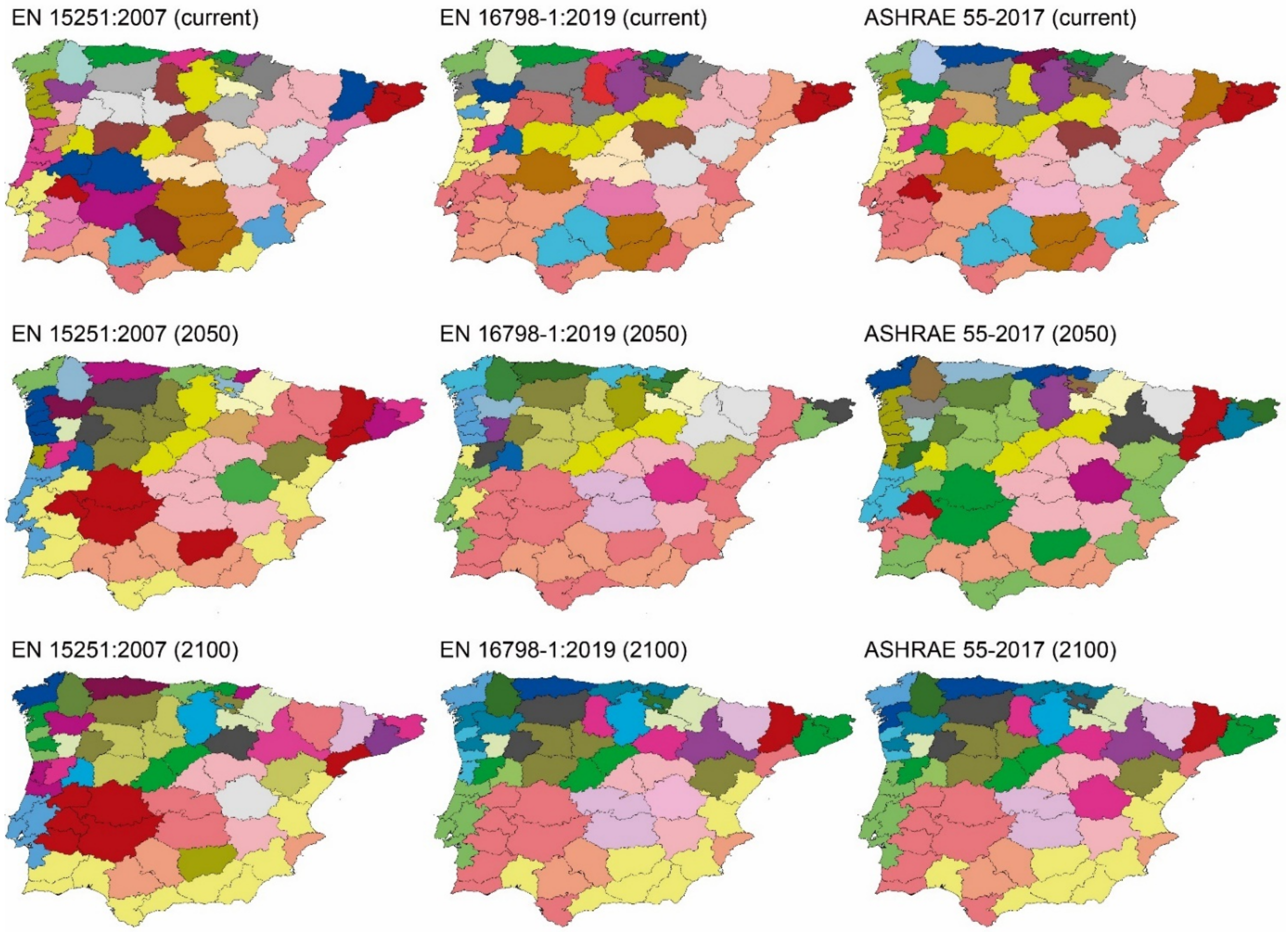

Fig. 11. Differences in the clusters obtained by the adaptive thermal comfort models: in the 3 periods of time analysed. The chromatic codification among the various maps is not the same due to the different clusters carried out in each model. It provides the reader with the cities which were grouped within a same group.

4. Conclusions

This research analyses the influence of using adaptive setpoint temperatures based on 3 different adaptive models of 3 adaptive thermal comfort standards (EN 15251:2007, EN 16798-1:2019 and ASHRAE 55-2017) in an office building located in 65 capitals of the Iberian Peninsula. The analyses were performed both in the current scenario and the years 2050 and 2100 in the scenario A2 according to the IPCC. Based on the results obtained by 780 various simulations, the following conclusions were drawn:

- The use of adaptive setpoint temperatures based on the model of the EN 16798-1:2019 standard was the option achieving a greater energy saving, both in the current scenario and the years 2050 and 2100, thus highlighting both the greatest saving achieved with the models carried out for a smaller zone of application (it is worth remembering that the ASHRAE 55-2017 standard has an international approach, whereas the EN 16798-1:2019 standard has been developed for the European continent) and the improvement in the energy saving with respect to the EN 15251:2007 standard (i.e., the previous standard).
- The greatest energy saving achieved with adaptive setpoint temperatures was obtained in those zones characterized by having a greater cooling energy consumption. This is due to the greatest incidence of this type of consumption in the countries in the south of Europe. Such energy saving strategy is therefore an opportunity to significantly reduce the energy consumption of office buildings by modifying the use of the HVAC system. In this sense, the cooling energy saving is greater in future scenarios than in the current one. This could have such a very significant impact on the energy efficiency in buildings, as this energy conservation measure could be applied to all building usages. Furthermore, the only requirements to apply it are the existence of an HVAC system, and some person in charge of changing the setpoint temperatures daily, so there would be no need to acquire any additional HVAC equipment. Another option to be considered is the use of a building automation system that could change setpoint temperatures daily, and even to coordinate this function with the opening of windows to work in mixed mode.
- The differences of energy consumption obtained between the adaptive models in the cities and years implied that clusters had differences among all cities, thus making impossible to establish zones of application of such strategies throughout the time. Moreover, the differences of energy consumption between the adaptive models in the cities and years generated that the clusters had differences, so the climate change scenarios are required to be considered to establish climate classifications. Also, the consideration of a greater approach with a larger number of case studies

and cities and other periods of time would lead to a homogeneous classification of the adaptive saving potential in the Iberian Peninsula.

To conclude, the results of this study give greater information about the possibilities of using adaptive setpoint temperatures in office buildings to achieve a high energy saving. The favourable results of the different cities show the possibilities of using such energy saving measures among various climate zones, although there are greater possibilities of energy saving the warmer the climate zone is. The results obtained can be useful for architects, engineers, and managers of office buildings to reduce the energy consumption, thus leading to a more sustainable performance for this type of buildings and guaranteeing a more rapid transition to the objectives proposed by the European Union: reducing greenhouse gas emissions by 2050. Future steps of this research will be focused on establishing an accurate application classification of adaptive strategies by increasing the number of cases and climate zones.

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Annex A

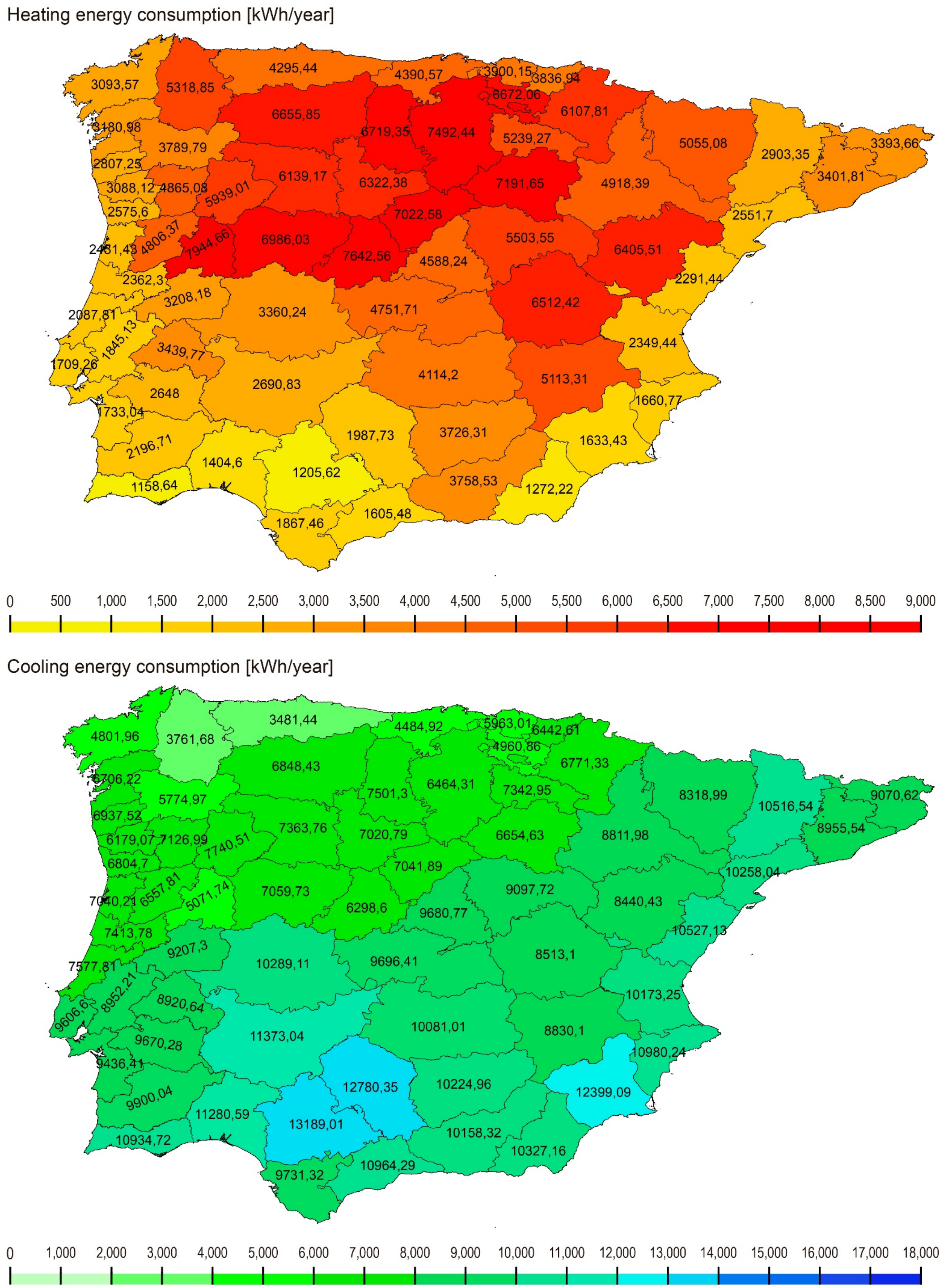


Fig. A1. Heating and cooling energy consumption by using static setpoint temperatures in the current scenario.

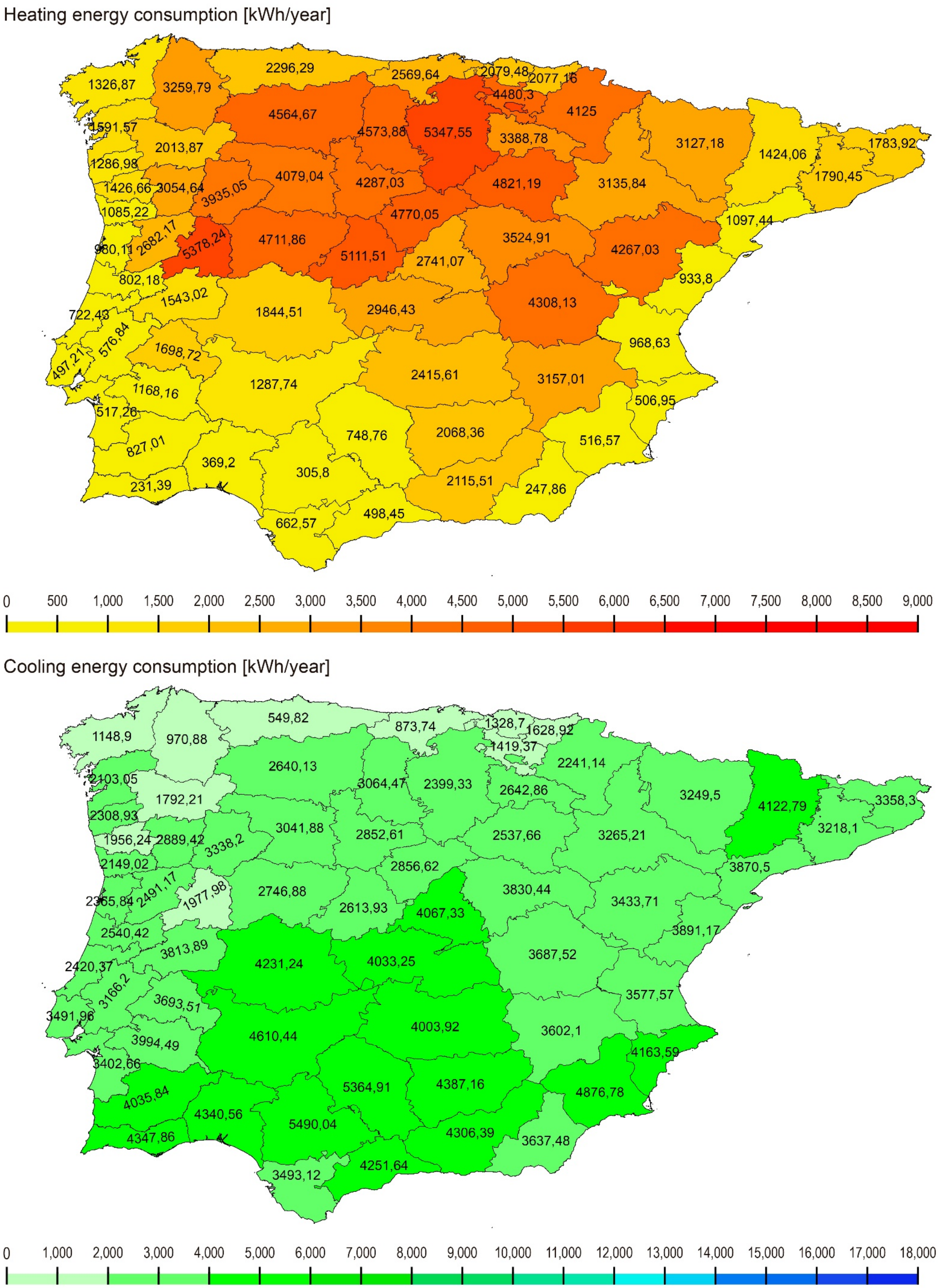


Fig. A2. Heating and cooling energy consumption by using setpoint temperatures in the current scenario according to the EN 15251:2007 standard.

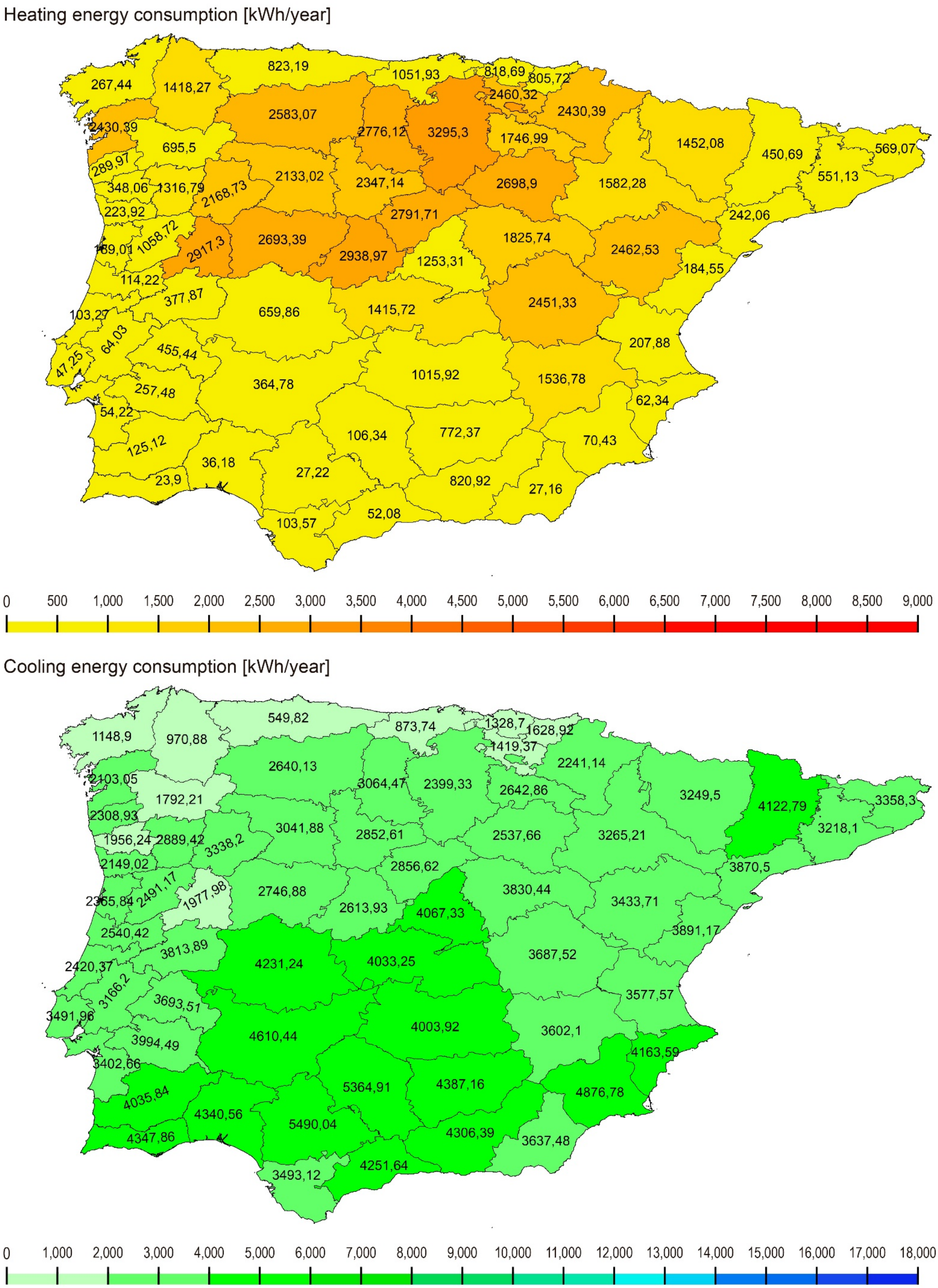


Fig. A3. Heating and cooling energy consumption by using setpoint temperatures in the current scenario according to the EN 16798-1:2019 standard.

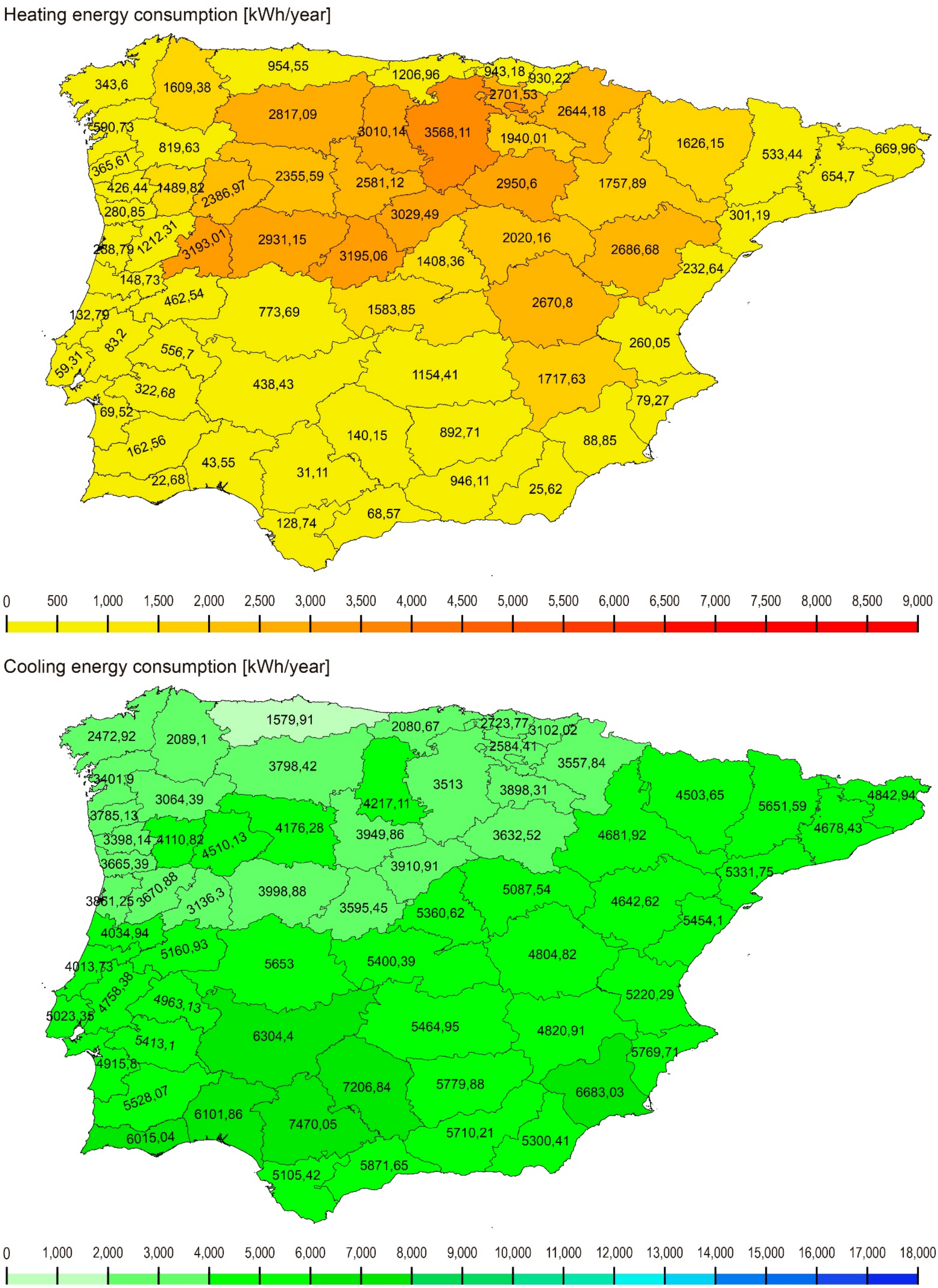


Fig. A4. Heating and cooling energy consumption by using setpoint temperatures in the current scenario according to the ASHRAE 55-2017 standard.

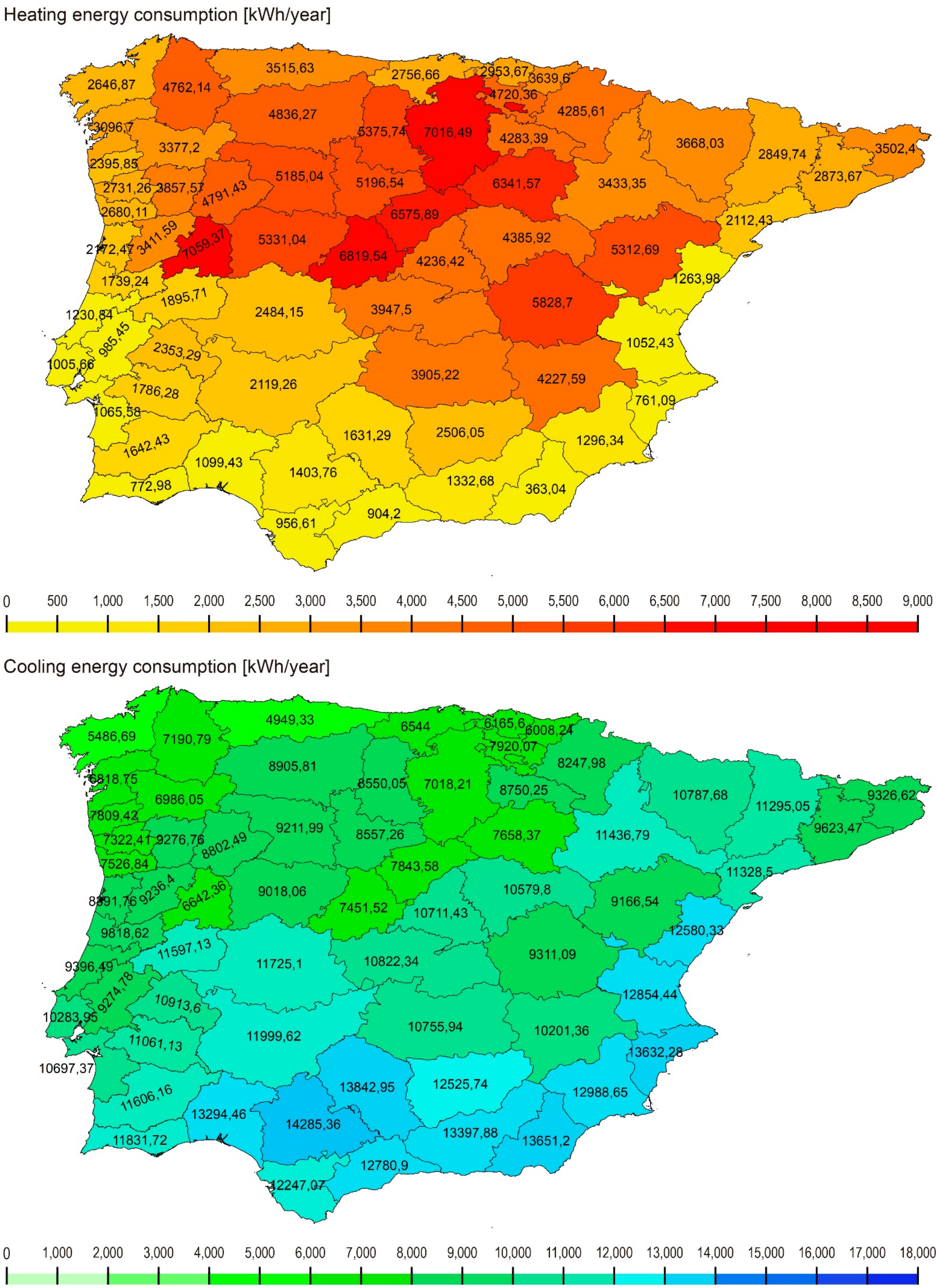


Fig. A5. Heating and cooling energy consumption by using static setpoint temperatures in the year 2050.

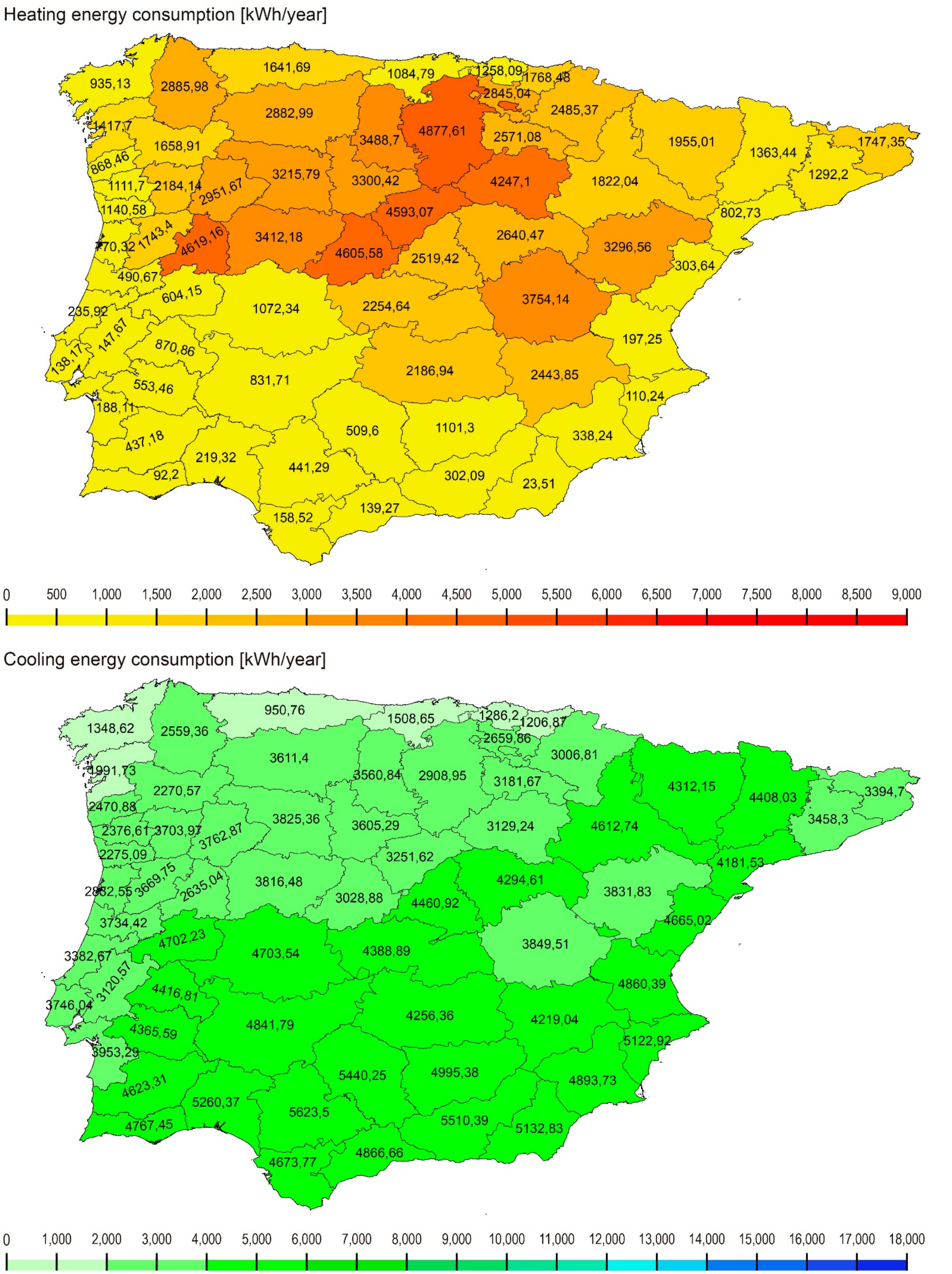


Fig. A6. Heating and cooling energy consumption by using setpoint temperatures in the year 2050 according to the EN 15251:2007 standard.

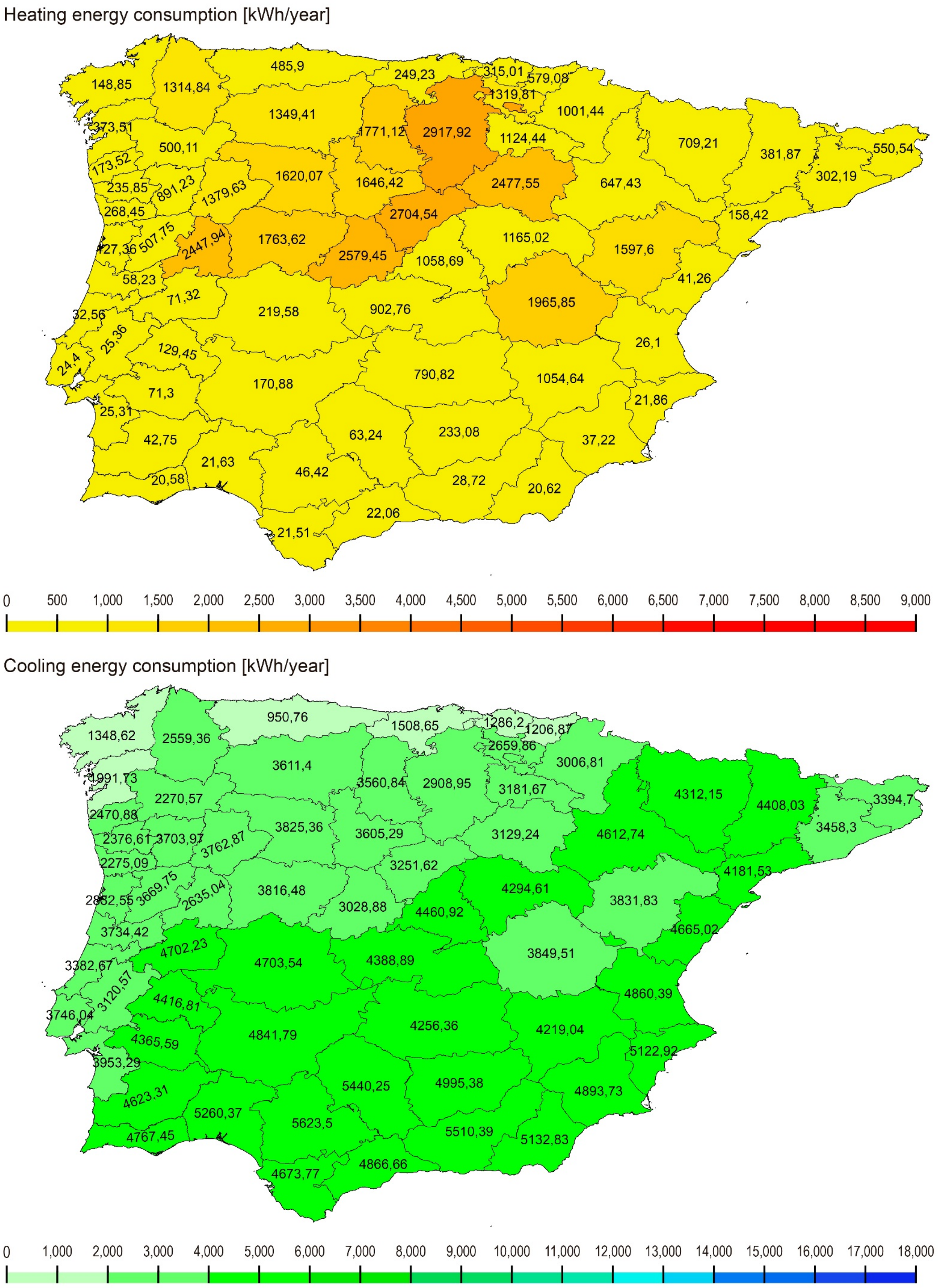


Fig. A7. Heating and cooling energy consumption by using setpoint temperatures in the year 2050 according to the EN 16798-1:2019 standard.

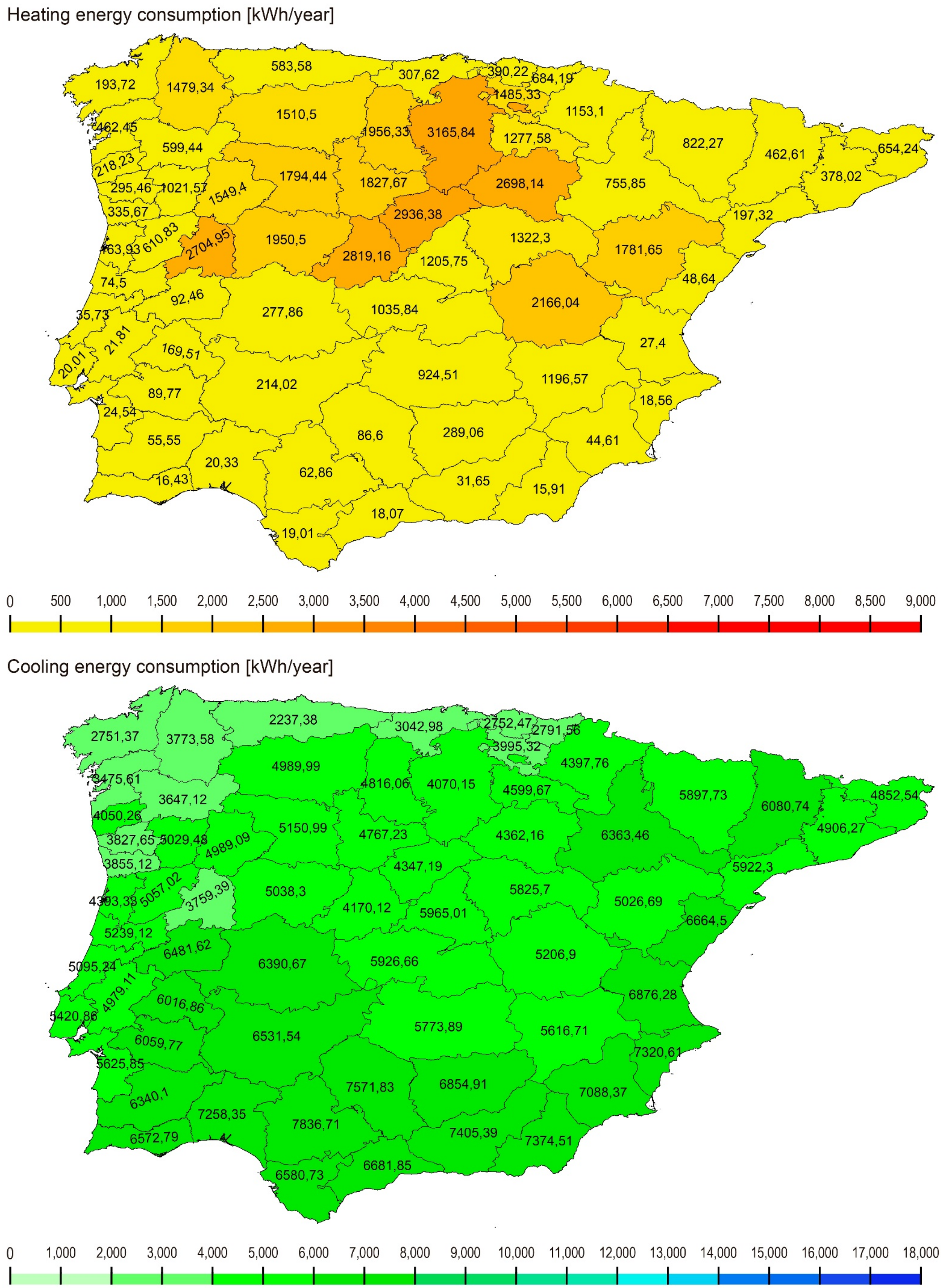
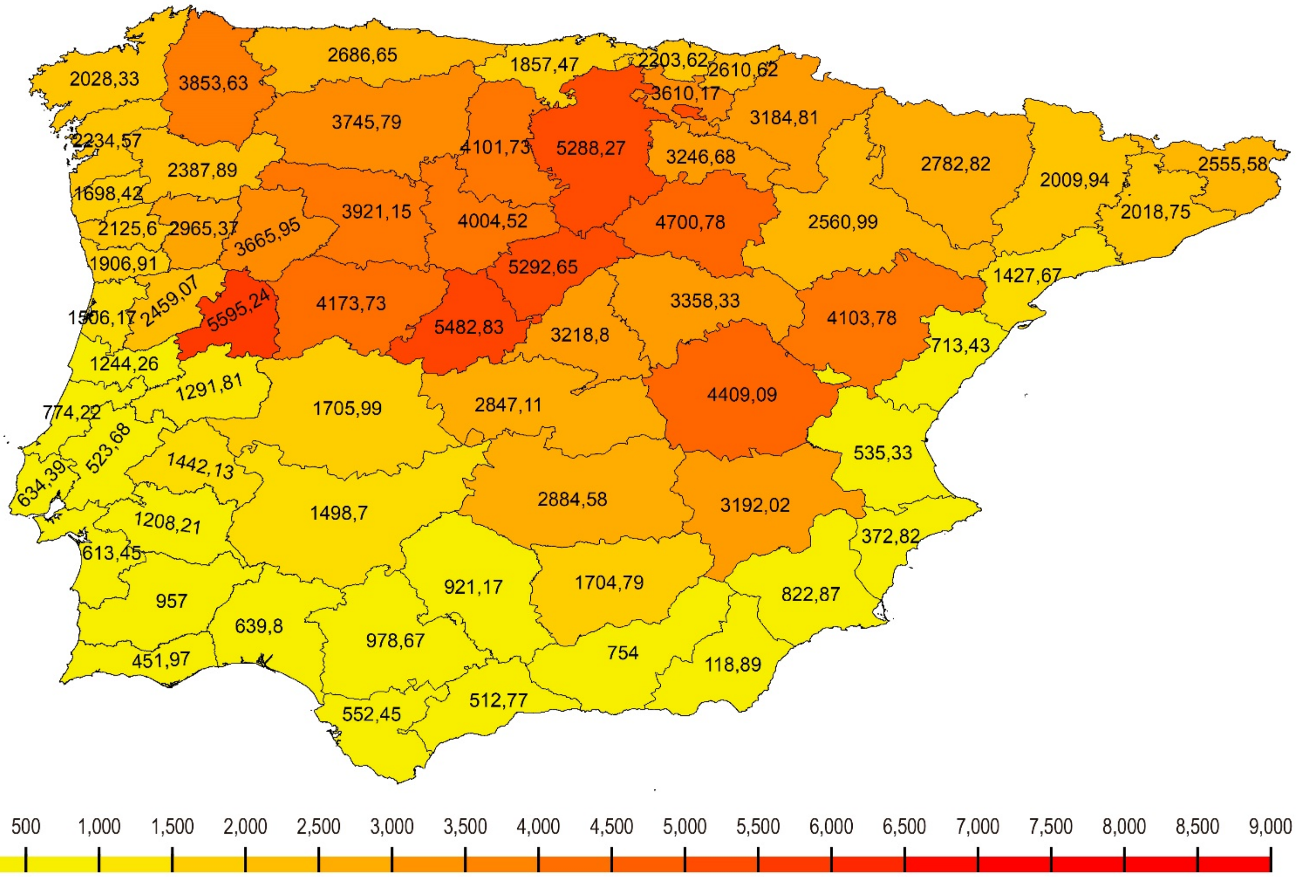


Fig. A8. Heating and cooling energy consumption by using setpoint temperatures in the year 2050 according to the ASHRAE 55-2017 standard.

Heating energy consumption [kWh/year]



Cooling energy consumption [kWh/year]

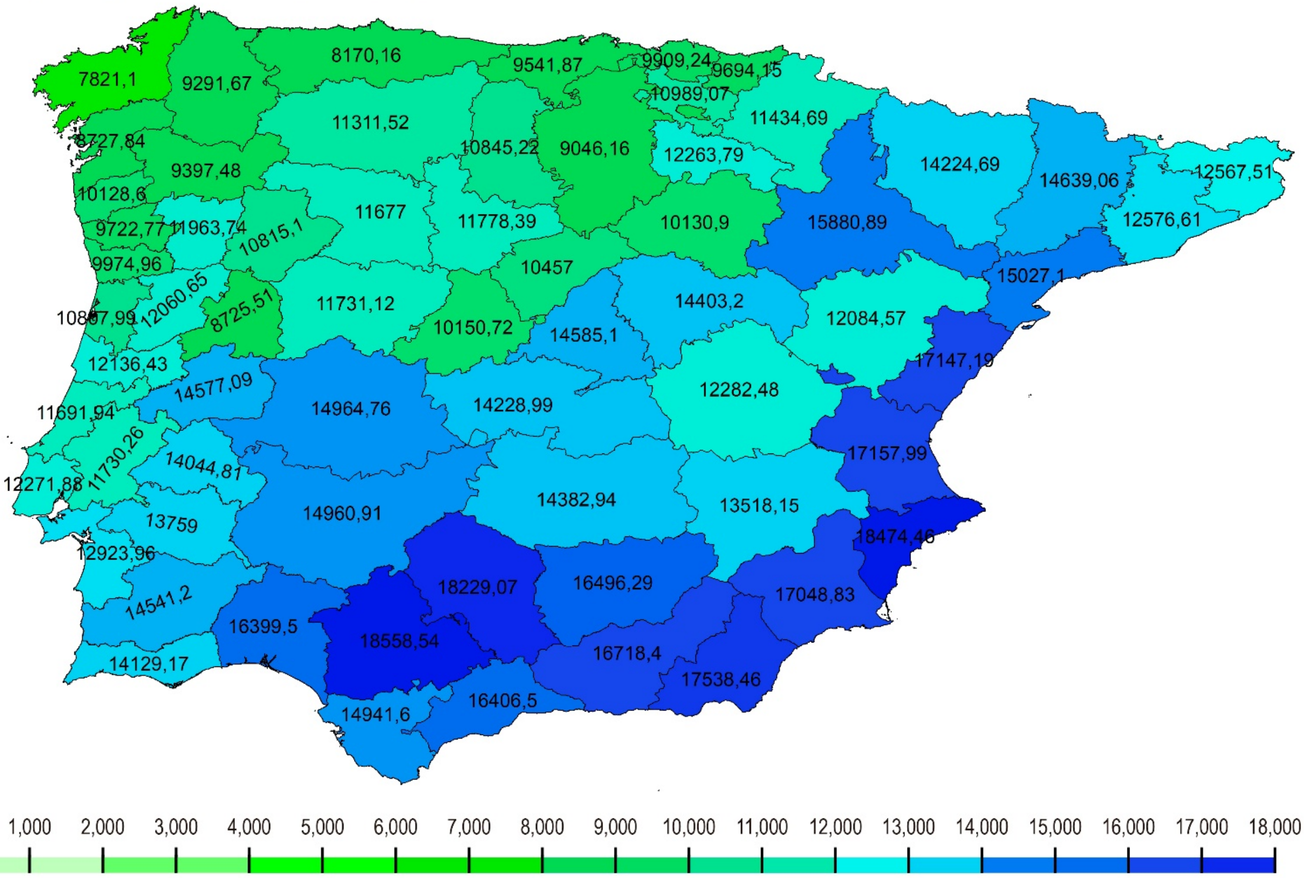


Fig. A9. Heating and cooling energy consumption by using static setpoint temperatures in the year 2100.

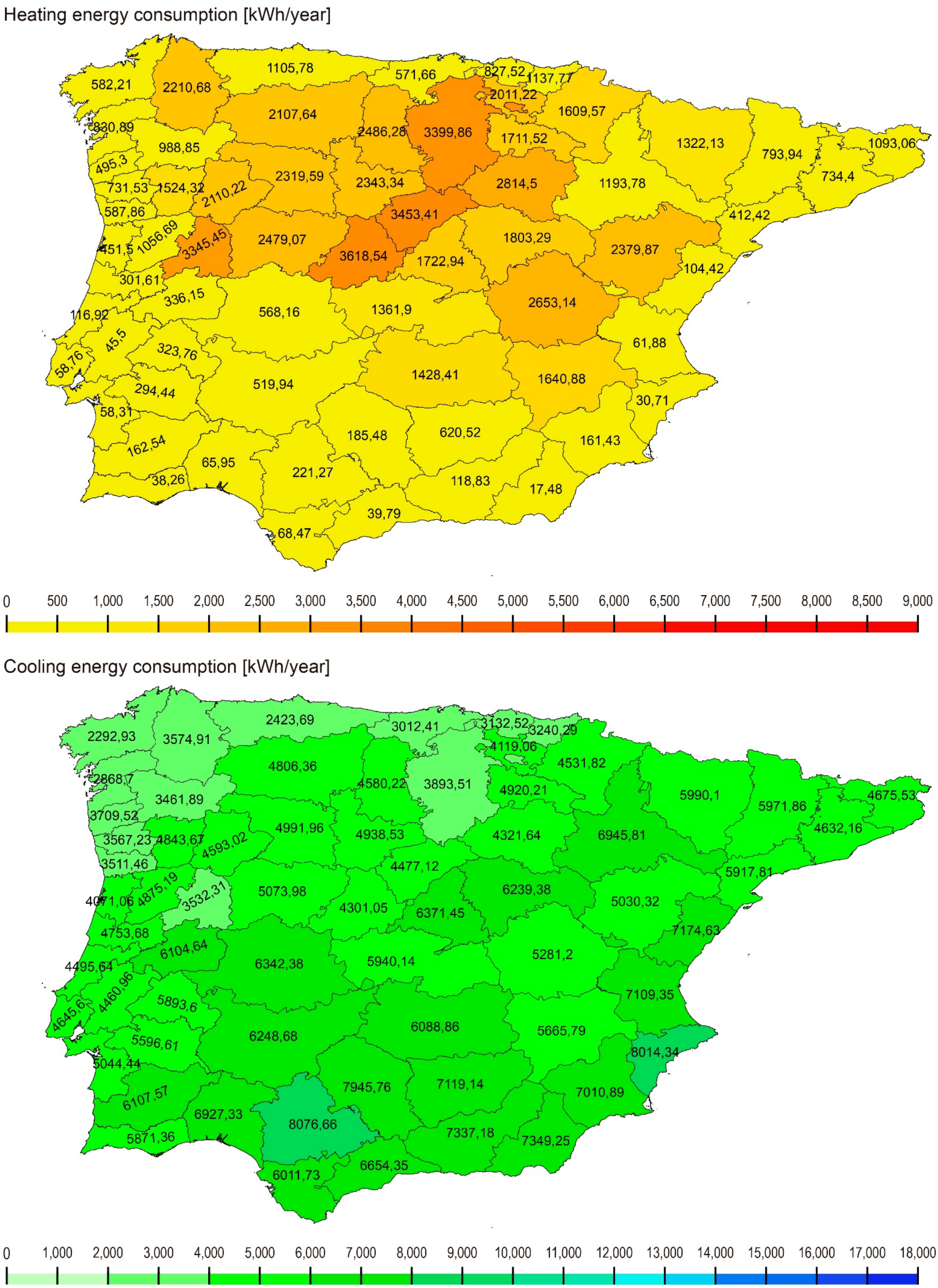


Fig. A10. Heating and cooling energy consumption by using setpoint temperatures in the year 2100 according to the EN 15251:2007 standard.

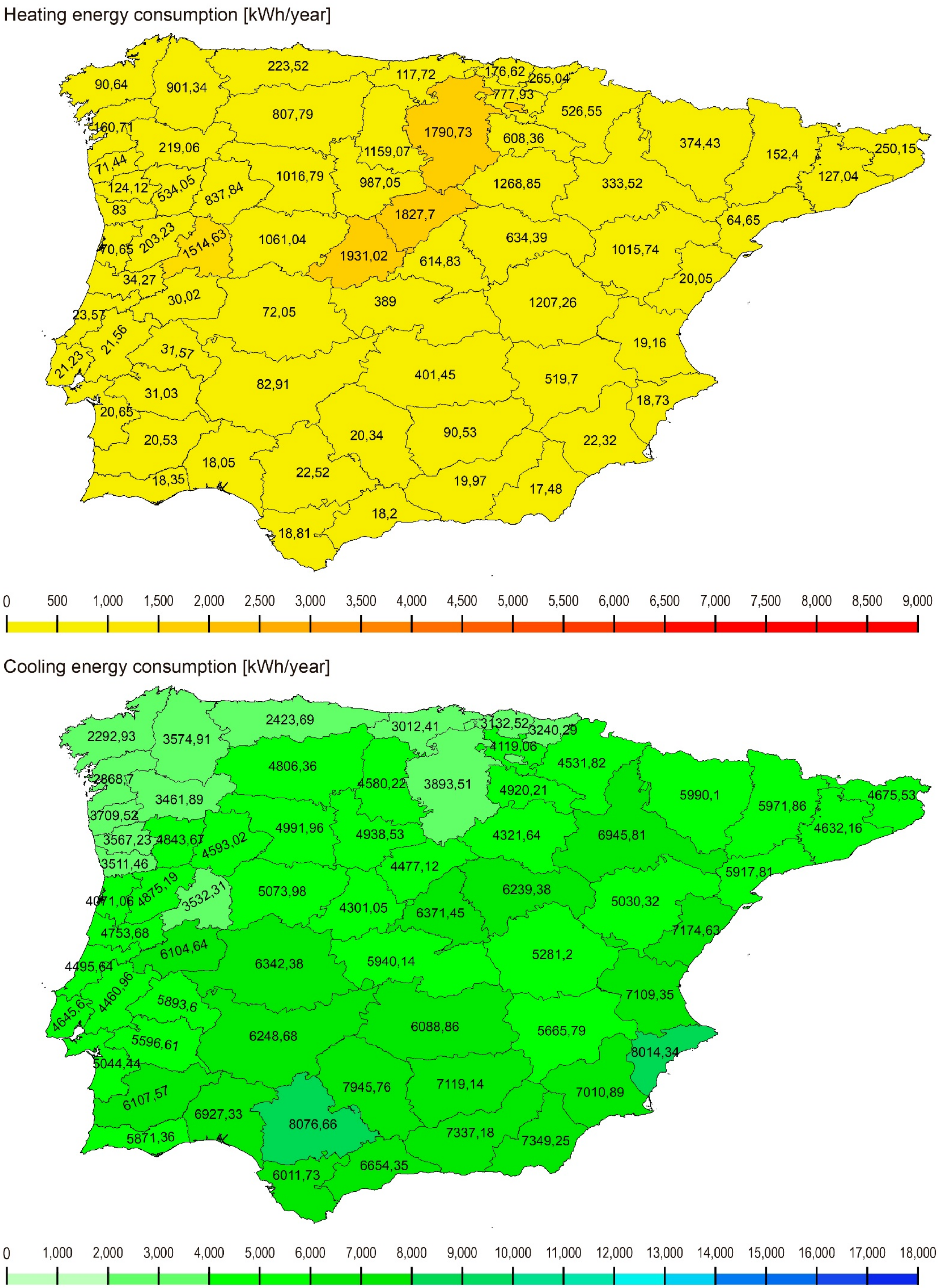


Fig. A11. Heating and cooling energy consumption by using setpoint temperatures in the year 2100 according to the EN 16798-1:2019 standard.

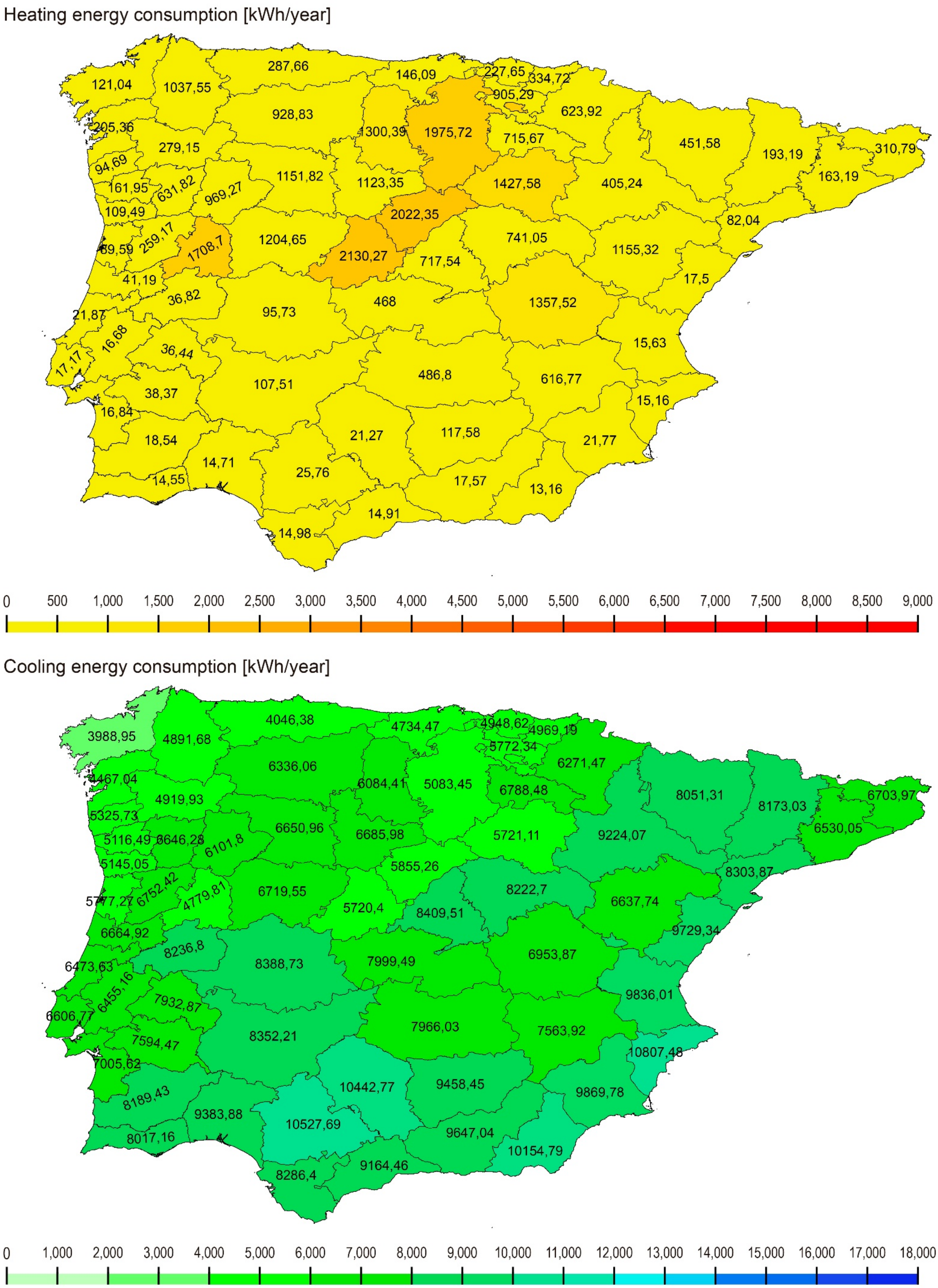


Fig. A12. Heating and cooling energy consumption by using setpoint temperatures in the year 2100 according to the ASHRAE 55-2017 standard.