Influence of climate on energy consumption and CO_2 emissions: the case of Spain

Abstract

This paper presents a methodology that allows for calculating the thermal and electric energy consumption together with CO_2 emissions of cities by inhabitant and household based on climate, only making use of publicly available data. With this aim, climate was analysed and cities were classified based on it. The analysis of those cities' energy consumption and CO_2 emissions allowed for drawing conclusions. Once aware of the climate zones in which energy consumption and emissions are higher, these mentioned conclusions could help to take further actions. An index has been defined to facilitate this analysis. This paper shows the case of Spain for illustrative purposes. This type of study has been carried out in some detail in many countries, but not in Spain yet. This paper tries as well to fill the existing gaps in studies that relate climate to thermal and electric energy consumption. For this purpose, it analyses the 145 cities in Spain that have more than 50,000 inhabitants. Knowing all this is essential in all regions and countries. It will allow for taking proper actions for promoting the energy saving and the use of alternative energy sources that reduce CO_2 emissions. According to the study carried out in this paper, the extremer the climate of a city is, the higher the thermal energy consumption is. This consumption decreases in softer climates. However, electric energy consumption is similar in all cities independent of the climate they have. With regard to CO_2 emissions, it was calculated that the higher the energy consumption of a city is, the higher these emissions are.

Keywords: Energy consumption, Emissions, Climate, Cities, Buildings, Spain

Introduction

Global urban population went from 2,300 million in 1994 to 3,900 million in 2014, meaning that more than half of the world inhabitants live in the cities. Moreover, predictions for 2050 expect that global population and cities total population will rise up to 9,600 million and 6,300 million, respectively. In other words, almost two-thirds of the population worldwide will be living in urban centres. The amount of people that live nowadays in the cities is even larger in some areas, such as Europe, North America, the Caribbean or Oceania. It reaches 70% in Europe and it is expected to get to 84% by 2050. And the number of cities with more than 10 million inhabitants went from 10 in 1990 to 28 in 2014 (Department of Economic and Social Affairs 2015). This demographical increase in the cities is a challenge in every sense and especially regarding energy consumption and environmental impact. More specifically, cities in Europe consume nearly 80% of the total energy used in the European Union. For this reason, cities are one of the focal points to be considered when energy policies or measures against climate change are being developed (Committed to local sustainable energy 2018). And within a city, buildings are particularly important as they are where these actions are carried out.

Electric and thermal energy in the form of natural gas are the two most common forms of buildings energy consumption (Shahrokni et al. 2014). For this reason, the aim of this paper is to analyse cities consumption of these types of energy and to relate it with their climate using the information published by countries' governments. This information is usually very dispersed. This way, it will not be necessary to spend time or money in surveys, inquiries or estimations to find out the areas that have the greatest energy consumptions. This study will help as well to take actions for saving energy, as well as to plan locations where to place the alternative energy sources required to meet the demand and reduce CO_2 emissions.

From the point of view of the electric energy consumption in relation to climate, the daily demand for electricity shows a seasonal pattern in the whole world. There are three different patterns depending on the time of year when the peak demand is reached. This happens during the winter in most European countries, except in Spain, Greece, Italy and Portugal, where an additional peak is observed throughout the summer months (Hekkenberg et al, 2009). Hong Kong (Al-Zayer and Al-Ibrahim 1996) or Thailand (Wangpattarapong et al. 2008) present patterns with peak demands only during the summer.

Climate variations have an influence on energy consumption, so many studies have been developed with regard how the increase of 1 °C in ambient temperature or urban warming influences the peak of electricity consumption or global consumption (Santamouris et al. 2015). These studies show that the demand for electricity and the ambient temperature share a nonlinear relation. In this way, the electricity consumption for heating grows when the ambient temperature decreases in winter, reason why this relation is negative. However, the mentioned relation is positive during the summer as the temperature increases and so does the electric energy consumption for air conditioning. All this creates an asymmetrical U-shaped curve in response to the difference between ambient temperature and the one considered as comfort temperature. This curve can vary depending on the climate zone. Its minimum value is observed when there is no need to use heating or air conditioners. Therefore, the electricity consumption is insignificant. Nevertheless, maximum values are observed when the ambient temperature is low in cold zones or high in warm areas.

To define that U-shaped curve it is necessary to estimate the influence of climate on the energy used for heating or cooling buildings. And this is precisely what most studies analyse. The degree-days method is used for it. It bases on the definition of the heating and cooling degree-days. The heating degree-days (HDDs) quantify the number of days in which the use of heating is necessary, reason why they indicate how severe the winter is. On the contrary, the cooling degree-days (CDDs) quantify the number of days in which the use of air conditioners is necessary. Therefore, they give an idea of the summer severity. This way it is possible to estimate the amount of energy that is required. The heating and cooling degree-days are defined as follows:

$$\text{HDDs} = \sum_{i=1}^{N} \left(T_b - T_{m,i}\right) \ (for\ T_{m,i} < T_b) \tag{1}$$

$$\text{CDDs} = \sum_{i=1}^{N} \left(T_{m,i} - T_b\right) \ (for\ T_{m,i} > T_b) \tag{2}$$

where N is the amount of days within the considered heating or cooling period, $T_{m,i}$ is the mean of the highest or lowest daily temperatures and T_b is the base temperature, under or above which the use of heating or air conditioning will be needed in the buildings. In other words, it is the temperature a building needs to reach its thermal balance with the energy it needs and the outside (Li et al. 2012).

Studies that relate electricity consumption to climate do so through temperature. These studies try to obtain a formula for relating energy consumption to temperature and to other complex variables. With this, the energy that will be consumed in the same analysed area is tried to predict; or when it is a whole country, its future consumption is calculated, but without taking into account the climatic differences that it may have, but rather it is considered as a whole. However, when the results are extrapolated to other areas with a different climate than the one studied, the conclusions obtained may not be correct, since it will depend on whether the climatic characteristics of the new study area are similar or not. However, unlike those studies this present paper does not try to obtain formulas to determine the consumption tendencies in certain areas, but to show the dependence of energy on climate. And, what is more important, its further application to the case of the Spanish cities that have more than 50,000 inhabitants, taking into account its climatic conditions. To the best of these author's knowledge, this has never been analysed so far: neither taking into account all the cities of a country, or carrying out the analysis according to its climate, nor such a large study in Spain. With this purpose, a simple procedure that uses publicly available data was deliberately chosen like in other studies (Urquizo et al. 2017; Hekkenberg et al. 2009). Moreover, a massive amount of data were used to draw conclusions. These conclusions will help getting familiar with the energy performance of cities depending on the climate they have.

The aim of this paper is to draw conclusions about energy consumption and CO_2 emissions of cities based on the climate zone they are located in. The awareness of the current situation will help figuring out the renewable energy systems that needs to be installed to eliminate pollutant emissions of buildings. Furthermore, governments will be able to enact laws to help reducing these emissions and companies will be able to deeply analyse cities to identify and plan their best investments. In other words, companies and public administrations will be able to achieve their goals, such as the ones related to reducing their consumption, the environment, climate change, greenhouse gases reduction, investment in new facilities, etc. Only by knowing the starting point can the final objective be reached by taking appropriate measures.

This paper is organised as follows: The "Literature review" section presents studies that relate energy consumption to climatic conditions; the “Methodology” section shows an overview of the proposed methodology, which can be applied to any country using the public and normally available information (general and statistical data); the “Application of the study to the case of Spain” section presents the application of the proposed methodology to the case of Spain; the “Results and discussion” section shows the results and proceeds with their discussion; lastly, the “Conclusions” section explains the conclusions drawn from this study.

Literature review

The review of the published literature will begin first with that corresponding to all countries except Spain, which will be carried out at the end of the section. In addition, the one corresponding to electricity consumption will be exposed first, then thermal consumption and finally CO_2 emissions.

The influence of different types of climate on energy consumption has not been specifically studied. On the contrary, the studies that exist are basically based on the prediction of electricity consumption from certain variables, mainly temperature. And it also happens, although to a lesser extent, with thermal consumption. The studies that exist are based mainly on the prediction of their consumption. In addition, there are hardly any studies that analyse the electrical and thermal consumption as a whole. Regarding CO_2 emissions, studies have analysed those produced in Chinese cities, and only very specifically in other countries.

Starting with the studies that analyse electricity consumption, Wangpattarapong et al. (2008) create two models to study the influence on the residential electricity consumption of Bangkok Metropolis. For one of them, it uses twenty-year data and is based on climatic factors such as relative humidity, rainfall, wind speed and CDD (it should be kept in mind that in Thailand the peak demand only occurs in summer). For the second model, five-year data were used and the number of air-conditioner sold, number of houses, population, income was taken into account, and again includes rainfall and CDD. The conclusion is that neither income nor population have an influence on electricity consumption. The business districts of Tokyo have been studied with a model based on degree-days and using one-year data. With it the electricity consumption is estimated from the temperature and humidity of the air. In addition, the sensitivity of electricity consumption to these variables is calculated (Ihara et al. 2008). The Eastern province of Saudi Arabia is studied based on the monthly electricity consumption of 5 years. Three models are obtained that relate the consumption to the degree-days: a linear model, another quadratic one and a sinusoidal third one, being the latter the one that generates the best approximation. The result obtained shows that electricity consumption is sensitive to temperature changes and that it behaves differently depending on whether it is the first or second half of the year (Al-Zayer and Al-Ibrahim 1996). Nasr et al. (2002) studied four different models of electricity consumption forecasting in Lebanon based on an artificial neural network with five-year data. The first of the models is based on previous consumption; the second also takes into account the degree days; the third uses the previous consumption and the gross domestic product; and finally, the fourth uses the four parameters together. Of all of them, the model that includes both the previous consumption and the degree-days is the one with the best forecast.

Electricity consumption in Europe has also been analysed. For Greece, the study of future electricity consumption has been developed taking into account a pessimistic and an optimistic scenario according to the Intergovernmental Panel on Climate Change, as well as a prediction of future climatic conditions. The model also takes into account the degree-days as well as the population and gross domestic product (Mirasgedis et al. 2007). One of the works that cover a wider geographical area is that of Bessec and Fouquau (2008) in which, based on 15-year data, the set of 15 European countries is studied, in addition to the 4 colder countries and the 4 warmer countries of that group. The study reaches the same conclusion obtained in other more geographically limited studies: there is a non-linear relationship between electricity consumption and temperature in Europe. In this case, it does not use the HDD and CDD variables for the linear model but a similar variable that it calls threshold variable.

With regard to the natural gas consumption of cities, it is basically used as a thermal source for heating, reason why it has a bigger influence on cold-weather zones. In the same way as the mentioned electricity studies, studies that connect natural gas consumption with climate are about demand prediction models in certain areas considering temperature factors. The analysis developed in the city of Szczecin (Poland) using data from two years in individual consumers and small industry allowed the prediction of natural gas consumption on one day of the year and at one hour of a day. The prediction was based on temperature and the method used an artificial neural network model. In this work it is recognised that to extrapolate the study to another area or city, a previous analysis must be carried out to adapt it to the new study (Szoplik 2015). Two studies have been developed for Turkey. One of them using also an artificial neural network technique, a model to forecast short-term natural gas consumption in Sarkya province (Turkey) was proposed. For this, data of air temperature, average cloud cover, relative humidity, atmospheric pressure and wind speed of 4 years were used (Taspinar et al. 2013). And the second one estimates the total consumption of natural gas by residential heating from that of certain cities. For this purpose, the use of the degree-days and the population was used (Sarak and Satman 2003).

The studies that have covered a greater geographical extension are those developed by Sailor and Muñoz (1997) and Sailor et al. (1998). The first, based on 10-year data, studies how electricity and natural gas are influenced by the climate in eight states of the United States that accounted for 42% of energy consumption in the United States. For the electric model the degree-days are used and for the natural gas model the temperature, relative humidity and wind speed. The results obtained show that for each state different parameters must be established in the models. The second study analyses the relationship between the consumption of natural gas and the climate in the residential and commercial sectors in the 50 states of the United States, also using 10-year data. To model the state's climate use the population-weighted average temperature and obtain a natural gas model with different parameters that depends on each state.

Other studies focus on the possible relation between different variables and energy consumption. These types of studies are the most common ones. Danish et al. (2018) analyse the nexus between energy consumption and financial development in Next-11 countries. Analysing data on economic growth per capita, globalisation and urbanisation from 1990 to 2014 concludes that financial development stimulates energy consumption. Nasreen et al. (2018) valuate the relationship between energy consumption, freight transport, and economic growth for 63 developing countries. For this, it divides the countries into three groups depending on the income level and analyses whether the relationship between the variables is unidirectional or bidirectional in each of these groups. The conclusion reached is that energy is important for economic activity. Liu (2018) examines the interaction between energy consumption and economic growth in China. The study is based on three models covering the period between 1982 and 2015. The conclusion reached is that the increase of any type of energy can increase China's economic growth in the long term.

Other studies relate energy consumption with non-economic variables. Ozturk (2015) analyses the relationship between energy consumption, air pollution, and climate change in six countries with data obtained for 22 years. The results show that energy consumption and air quality are positively related to climate change. Ashouri and Rafei (2018) study the effects of the consumption of energy and water resources on air pollution in Iran with data of 43 years. It is concluded that both have an influence on CO_2 emissions. Other studies focus only on the relation of the electric energy consumption in particular and other variables. Balcilar et al. (2019) explore the relationship between electricity consumption, real gross domestic product, and CO_2 emissions in Pakistan with data of 43 years too. The results show unidirectional causality running from economic growth to electricity consumption and from this to CO_2 emissions. Zhong et al. (2019) analyse the relationship between electricity consumption, economic growth, and employment in China. The study shows the great importance of electricity in China's economic growth.

Regarding CO_2 emissions, the cities that have been most analysed are those of China since this is a priority aspect for their government. To perform the analysis in Guangdong, Hong Kong and Macao Greater Bay Area cities, the fossil fuel-related emission and those corresponding to those produced by the 7 production processes that generate more than 95% of total emissions in China have been considered. Its evolution has been analysed from 2000 to 2016 and compared with total emissions from China (Zhou et al. 2018). A similar study has been developed in 24 cities in China analysing 17 fossil fuel and 9 industry products (Shan et al. 2017). In China, emissions from 183 cities have also been studied. One of the main problems encountered is the lack of available energy data. Emissions are affected by characteristics such as population size, industrial structure and government policies (Chen et al. 2017). Spatiotemporal variations in China have also been studied. For this, population size, industry, gross domestic product, capital investment and even foreign direct investment have been taken into account. All selected variables positively influence CO_2 emissions, except the last one that does so negatively (Wang and Xiaoping 2017). Another study in 30 cities in China from 1990 to 2010 showed that the growth of cities impacts on the increase in emissions (Fang et al. 2015). A comparative analysis between the emissions of 4 Chinese cities versus 22 European cities concluded that Chinese cities produce higher per-capita emissions than the European cities (Yu et al. 2012). In 10 Chinese cities their emissions were analysed and the contribution of each of the sectors was obtained. It was concluded that emissions from Chinese cities were higher than the average of 10 other cities in different parts of the world (Wang et al. 2012).

Regarding other countries, in Japan, CO_2 emissions and their urban form have been studied in 50 cities with similar socio-economic attributes. The results indicate that more populated and less dense cities produce more emissions (Makido et al. 2012). In the United States, a study was conducted in the city of Indianapolis to calculate CO_2 emissions. For this, a building energy simulation model was used, as well as local air pollution, traffic data and power production data (Gurney at al. 2012). Therefore, worldwide it is almost exclusively in China where knowledge of CO_2 emissions in cities has been a priority.

The objective of published studies that relate electricity consumption and climate in Spain is to calculate the prediction of electricity demand. Moral-Carcedo (2005) typifies the nonlinearity of the demand response to temperature variations using the degree-days and analysing three different models. Pardo et al. (2002) also make use of the degree-days to predict the electrical load based on increases of temperature, concluding that heating degree-days are the ones that most affect in Spain (it should be kept in mind that in Spain there is also a peak demand in summer). Valor et al. (2001), through the degree-days, study the correlation between electricity load and daily air temperature to predict electricity consumption. Cancelo et al. (2008) discuss the model used by the Spanish system operator in short-term electricity load forecasting. The model used is for forecasting the daily load up to ten days ahead and hourly predictions for horizons up to three days. In both cases the model is the same, but its parameters are changed. In a study covering five countries of the European Union, including Spain, Pilli-Sihvola et al. (2010) study the impact of climate change. The analysis is based on how temperature changes affect the necessity of heating and air conditioning. For this, the relationship between temperature variation and electricity consumption is estimated.

With regard to studies concerning natural gas in Spain, there is only one that relates natural gas consumption to ambient temperature (Sánchez-Úbeda and Berzosa 2007). It analyses the model used by the technical manager of the Spanish gas system to make a prediction of the industrial end-use natural gas consumption in a medium-term horizon of 1-3 years with a resolution of days.

As with thermal studies, those related to CO2 emissions are very scarce for Spain. In the case of Madrid, from the knowledge of the existing residential air conditioning units, an approximation of their electricity consumption and CO2 emissions is obtained. The results are obtained from an analysis of the thermodynamic air conditioning cycle (Izquierdo et al. 2011). Gutierrez et al. (2007) propose a model to predict global emissions in Spain with emissions data from cement manufacturing, fossil-fuel burning and natural gas flaring from 1986 to 2002. Regarding the emissions of the service sector, Alcántara and Padilla (2009) develop an analysis by means of its decomposition in its different branches. The conclusion that is obtained is that the transport activities are those that cause the greatest amount of emissions, but there are other services, such as hotels and restaurants, public administration, wholesale and retail trade, and real estate, and renting and business activities that have a lot of influence and which however are given little importance.

Therefore, the lack of studies developed at the level of a whole country and more specifically in Spain is confirmed. The aim of this paper is to address this deficit.

Methodology

Fig. 1 shows a flowchart of the proposed methodology that helps easily understanding it. Total consumptions and consumptions per household and inhabitant of each climate zone are obtained on the basis of each country available information (statistical population data and thermal and electric energy consumption data). This allows for the analysis by climate. CO_2 emissions are calculated next with the aim of finding out how much renewable energy is required to eliminate pollutant emissions.

Fig. 1 Methodology flowchart

Climate classification of a country

Climate is defined as the weather conditions prevailing in an area in general or over a long period (Oxford Living Dictionaries, 2019). Several rates have been defined to characterise it. They classify a specific area by atmospheric parameters: annual average temperature, monthly average temperature, annual total precipitation, monthly precipitation, thermal range, latitude, etc. The most common ones are:

- Lang's index: $I_l = p/t$, where p is the annual total precipitation in millimetres and t is the annual average temperature in Celsius degrees. Climate is considered arid for values between 0 and 40; humid between 40 and 160; and superhumid for values higher than 160.
- Martonne's index: $I_m = p/(t+100)$, where p is the annual total precipitation in millimetres and t is the annual average temperature in Celsius degrees. A zone is considered arid for values between 0 and 5; semi-desert between 5 and 10; Mediterranean semi-arid between 10 and 20; subhumid between 20 and 30; humid between 30 and 60; and superhumid for values higher than 60.
- Dantín – Revenga's index: $I_{dr} = 100*t/p$, where p is the annual total precipitation in millimetres and t is the

annual average temperature in Celsius degrees. A zone is considered humid for values between 0 and 2; semi-arid between 2 and 3; arid between 3 and 6; and semi-desert for values higher than 6.

- Currey's index: $I_c = A/(1+(1/3)L)$, where A is the thermal range and L is the Weather Station's latitude. A zone is considered hyperoceanic for values between 0 and 0.6; oceanic between 0.6 and 1.1; subcontinental between 1.1 and 1.7; continental between 1.7 and 2.3; and hypercontinental for values higher than 2.3.
- Kerner's index: $I_k = (T_{oct}-T_{apr})*100/A$, where T_{oct} is the average temperature in October, T_{apr} is the average temperature in April and A is the thermal range. A zone is considered continental for values close to 0; and oceanic for values close to 100, although it is considered oceanic starting at 30.
- Köppen's classification: It bases on monthly average values of precipitations and temperatures to define the different types of climate, and it establishes thresholds for precipitation and temperatures based on the impact they have on the vegetation distribution and human activity. Depending on temperatures, climate can be divided in five different groups: warm climate or Type *A*, in which there are no temperatures under 18ºC; dry climate or Type *B*, that can be steppe or desertic (it is represented with an additional letter, *S* or *W*, respectively), and in which evaporation exceeds the annual average rainfall; temperate climate or Type *C*, in which the coldest month has temperatures between 0ºC and 18ºC; cold climate or Type *D*, in which average temperatures are lower than 0ºC during the coldest month and greater than 10ºC during the warmest one; polar climate or Type *E*, in which during no month temperatures reach 10ºC. Groups *A*, *C* and *D* are divided in four different subgroups represented by small letters: *f*, if climate is humid during the whole year; *w*, if winter is the driest season; *s*, if the driest season is the summer; and *m*, for very rainy forests. An additional small letter completes this classification: *a*, for very warm summers with temperatures higher than 22ºC; *b*, for warm summers, having the warmest month temperatures below 22ºC; *c*, for cool short summers; *d*, for very cold winters, with temperatures around -38ºC during the coldest month; *h*, for warm dry climates, with an annual average temperature greater than 18ºC; and *k*, for cold dry climates, with an annual average temperature lower than 18ºC (Agencia Estatal de Meteorología, 2018).

These three first indexes are aridity indexes. Water scarcity, air humidity or soil moisture can be calculated with them. The fourth one is a continentality index, which is applied in places where marine influence is scarce and therefore present low rainfall amounts and a high thermal range. The fifth index is an oceanity index. It indicates the proximity of a place to the sea. This implies that temperatures are moderate and that humidity and precipitations increase. Finally, Köppen's classification is one of the most used ones all over the world. Most countries base on it for creating their climate maps.

Classification of cities by climate

The first step is to select the cities that will be the scope of this study. The choice can be made basing on different factors. For instance, cities with a specific number of inhabitants, cities located in a particular area of a country or cities with other characteristics that are interesting for analysing their energy consumption base on their climate. The next step is to identify their UTM coordinates and to locate them in the map. This step leads to the identification of their climate. For those cities located in the interzonal boundaries and whose climates may not be so clear, the use of one of the previous indexes is required to properly identify their climate. For example, their climate can be assigned using Martonne's index.

Thermal and electric energy consumption

Cities have been considered as a centre where people do their daily activity. Consequently, the energy consumed in them that was considered in this paper is the one related to this activity, except for the energy associated with industrial activity and means of transport. Industrial activity was not taken into consideration to avoid distorting cities energy use, since it depends on the city level of industrialisation, and therefore, on a higher or lower energy consumption. Moreover, it is not possible to separate the tertiary sector values from the rest considering the way that official organisations group some of their data. For these reasons, the existing homes, shops and administrative offices were the ones considered for calculating the electric and thermal energy consumed in the cities. This energy is considered to be the one needed for a city daily activity, and so it is related to all residents that live there. The bigger a city is, the more shops and administrative offices it has. Therefore, each home will have assigned its own energy use, as well as an additional consumption related to stores and offices. This last consumption is not directly consumed by residents for their particular use, but they need it to live in the city.

Information and statistical data regarding population and households of each city is used for calculating the thermal and electric energy use. Energy consumption data are itemised or grouped by zones depending on each country. For this reason, before being able to analyse these data by climate a previous work on these values is required to obtain the total energy consumptions and consumptions per household and per inhabitant. The following divisions of the Statistical Classification of Economic Activities in the European Community, commonly referred to as NACE (for the French term "nomenclature statistique des activités économiques dans la Communauté européenne") (Eurostat Methodologies and Working Papers 2008), has been considered for the electric energy consumption: 36 to 39, 53, 60, 61, 72, 84 to 88 (exc. 85.5 and 85.6), 91, 99, 45 to 47, 58.2, 59, 62 to 71, 73 to 75, 77 to 82, 85.5, 85.6, 90, 92 to 98. Data related to the thermal energy consumption are those referring to natural gas consumption with pressures equal or less than 4 bar. They correspond to homes, shops, public administrations and services consumptions. Most part of their consumption is between 5,000 and 50,000 kWh per year.

CO_2 emissions

CO_2 emissions produced through electric energy consumption depend on the mix of a country's electric energy consumption. For this reason, values of these type of emissions can be obtained using this information. In the same way, information about the thermal energy consumption allows for obtaining values of CO_2 emissions produced by it.

Application of the study to the case of Spain

Due to the few studies that study the influence of climate on energy consumption in Spain, this section applies the suggested methodology to the particular case of Spain. Energy consumption of Spanish cities was never studied in detail before taking climate into consideration. The scope of this study includes all Spanish cities with populations of more than 50,000 inhabitants. Geographical scope is the whole country.

Climate classification of Spain

The State Meteorological Agency of Spain (AEMET) used Köppen's climate classification for delimiting Spain by types of climate. This agency created the climate map shown in Fig. 2. It is presented in its original version (Instituto Geográfico Nacional 2018).

Classification of Spanish cities by climate

Spain has a total population of 46.5 million people. 24.5 million of these people live in cities with more than 50,000 residents, which is more than 50%. More than 9 million people live in the 10 most populated cities of Spain. It represents nearly 20% (Instituto Nacional de Estadística 2018 a). This brings to light the importance that cities have in Spain and the benefits it brings knowing their energy consumption. It helps identifying where to take actions to reduce consumption and CO_2 emissions, as well as planning facilities to cover cities energy needs. Spanish cities with more than 50,000 inhabitants amount to 145.

Considering both the location of these Spanish cities and the Spanish climate map, it was observed that none of them has mountain climate. Therefore, this type of climate will not be used. Furthermore, due to the similarities they share and with the purpose of making more general groups for this study, the four different types of climate of the Canary Islands will be grouped in one only type of climate called subtropical. Continental Mediterranean, warm interior Mediterranean and transition oceanic climates will be likewise grouped in one only type of climate, named continental. Therefore, this study will consider the five following weather groups: oceanic, continental, Mediterranean, semi-arid and subtropical. Their legends are shown at the left side of Fig. 2.

Fig. 2 Climate map of Spain

Table 1 shows in alphabetical order the classification by climate of these 145 Spanish cities with more than 50,000 residents. The map presented in Fig. 2 was used to identify the zone to where each city belongs to. In addition, Martonne's index needed to be calculated for a proper classification of cities located in interzonal boundaries. Table 1 has been created this way.

Cities with oceanic climate are those situated in the coastal zones of Galicia and the North of Spain. Their climate is characterised by mild average temperatures, limited thermal range and high rainfall. This is due to the influence of the Atlantic Ocean, which brings rainy prevailing winds and depressions that travel along this region during the whole year, but specially during the winter. Most part of Spain have continental climate. The continental climate is observed in the centre of the Iberian Peninsula and it is characterised by a great thermal range, limited rainfall and extreme temperatures during the winter, during the summer or during both seasons. The whole area with Mediterranean climate is not wide. Almost the whole Mediterranean coast, the Balearic Islands and the Atlantic coast of Andalusia share this type of weather. However, the number of cities with Mediterranean climate is comparable to the number of those that have continental climate. Soft winters, warm summers and limited rainfall are typical of the Mediterranean climate. Whereas precipitations decrease normally from north to south, temperatures decrease from south to north. However, there is a diversity of microclimates defined by topography, latitude and distance from the sea. The semi-arid climate is located in the south-east from Spain, which is the least rainy region of Europe. Temperatures are gentle in winter and warm in summer. Precipitations are so scarce they have water deficit during most part of the year. Finally, the Canary Islands have a subtropical climate, reason why they present cool temperatures with several dry months and humidity. This humidity comes from either the rain or the fog due to the islands' topography and it is the reason for water drops falling to the ground.

Thermal and electric energy consumption of Spanish cities

This analysis bases on the official data of 2016. Data was obtained from the Spanish National Statistics Institute (Instituto Nacional de Estadística 2018 b), the National Commission on Markets and Competition (Comisión Nacional de los Mercados y la Competencia 2017) (they both depend on the Ministry of the Economy, Industry and Competitiveness); and the Secretariat for Energy, which depends on the Ministry for the Ecological Transition (Secretaría de Estado de la Energía 2018). Each Spanish province provide information regarding its own energy consumption. Cities of a province share the same type of climate and therefore they present similar energy consumptions. For this reason, the best way to proceed is to use the population statistical data to calculate cities consumptions.

CO_2 emissions of Spanish cities

Spanish government set CO_2 emission factors basing on the Directive 2010/31/UE of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings. These factors are the ones to use regarding the buildings sector (Ministerio de Industria, Energía y Turismo & Ministerio de Fomento, 2016). It establishes the natural gas CO_2 emission factor as 0.252 tCO_2/MWh. In the same way, it establishes CO_2 emissions as 0.291 tCO_2/MWh for electricity points of consumption considering all types of generators and sources.

Table 1 Classification of cities by climate

Type of climate	Cities
Continental	Albacete, Alcalá de Guadaíra, Alcalá de Henares, Alcobendas, Alcorcón, Aranjuez, Arganda del Rey, Ávila, Badajoz, Boadilla del Monte, Burgos, Cáceres, Ciudad Real, Collado Villalba, Córdoba, Coslada, Cuenca, Dos Hermanas, Fuenlabrada, Getafe, Girona, Granada, Guadalajara, Huesca, Jaén, Leganés, León, Linares, Lleida, Logroño, Madrid, Majadahonda, Mérida, Móstoles, Ourense, Palencia, Pamplona/Iruña, Parla, Pinto, Ponferrada, Pozuelo de Alarcón, Rivas-Vaciamadrid, Rozas de Madrid (Las), Salamanca, San Sebastián de los Reyes, San Vicente del Raspeig, Segovia, Sevilla, Talavera de la Reina, Toledo, Torrejón de Ardoz, Utrera, Valdemoro, Valladolid, Vélez-Málaga, Vitoria/Gasteiz, Zamora, Zaragoza
Mediterranean	Alcoy/Alcoi, Algeciras, Badalona, Barcelona, Benalmádena, Benidorm, Cádiz, Castelldefels, Castellón de la Plana, Cerdanyola del Vallès, Ceuta, Chiclana de la Frontera, Cornellà de Llobregat, Estepona, Fuengirola, Gandía, Granollers, Huelva, Jerez de la Frontera, L'Hospitalet de Llobregat, Línea de la Concepción (La), Málaga, Manresa, Marbella, Mataró, Melilla, Mijas, Mollet del Vallès, Motril, Palma de Mallorca, Paterna, Prat de Llobregat (El), Puerto de Santa María (El), Reus, Rubí, Sabadell, Sagunto/Sagunt, San Fernando, Sanlúcar de Barrameda, Sant Boi de Llobregat, Sant Cugat del Vallès, Santa Coloma de Gramenet, Tarragona, Terrassa, Torremolinos, Torrent, Valencia, Viladecans, Vilanova i la Geltrú, Vila-Real
Oceanic	A Coruña, Avilés, Barakaldo, Bilbao, Ferrol, Getxo, Gijón, Irún, Lugo, Oviedo, Pontevedra, San Sebastián/Donostia, Santander, Santiago de Compostela, Siero, Torrelavega, Vigo
Semi-arid	Alicante/Alacant, Almería, Cartagena, Ejido (El), Elche/Elx, Elda, Lorca, Molina de Segura, Murcia, Orihuela, Roquetas de Mar, Torrevieja
Subtropical	Arona, Arrecife, Las Palmas, San Bartolomé de Tirajana, San Cristóbal de la Laguna, Santa Cruz de Tenerife, Santa Lucía de Tirajana, Telde

Results and discussion

The main statistical data of the total, thermal and electric energy consumption are presented for each climate zone:

Number of cities:
$$n_i = \sum_j 1 \tag{3}$$

Mean:
$$\bar{E}_i = \sum_j E_{ij} \tag{4}$$

Standard deviation:
$$s_i = \sqrt{\frac{\sum_{ij}(E_{ij} - \bar{E}_i)^2}{(n_i - 1)}} \tag{5}$$

Median: $Median_i = \left[\frac{n_i+1}{2}\right] th$ term if the total number of the elements is an odd number, otherwise $Median_i = \frac{\left(\frac{n_i}{2}\right)th\text{ term} + \left(\frac{n_i}{2}+1\right)th\text{ term}}{2}$ (6)

Maximum: $$E_{i\,max} = \max(E_{ij}) \quad (7)$$

Minimum: $$E_{i\,min} = \min(E_{ij}) \quad (8)$$

where n_i is the number of cities that share the climate i; $\bar{E}_i$ is the mean energy consumed in the climate zone i; E_{ij} is the energy consumption of the city j, which is located in the climate zone i; s_i is the standard deviation of the energy consumed in the cities of the zone with climate i; the energy consumed will be total, thermal or electric depending on the case of study; and cities consumptions should be in ascending order for calculating the median.

An index for climates was defined in this study analogous to the one in Valor et al. (2001) for monthly electric energy consumption. Its aim is to analyse fluctuations in consumptions of each climate zone. The climate variation index (CVI) is defined as follows:

$$CVI_i = \bar{E}_i / \bar{E} \quad (9)$$

where CVI_i is the index for a climate i, $\bar{E}_i$ is the energy consumption mean value in the climate zone i and $\bar{E}$ is the mean energy consumption of all cities (of all climate zones). This index allows for an easy analysis of the climate zones whose cities present the greatest energy consumptions.

Sample of study

Results are presented according to the five different climate groups defined in "Classification of Spanish cities by climate" section. Cities thermal and electric energy consumption was considered, including consumption of homes, shops, administrative offices and public services. Data provided by official organisations was handled with the aim of getting the results explained in this section. Data of official organisations were not presented in the same way they do in this paper. Another piece of information to take into consideration regarding all results is that there are two cities with distinctive features: Madrid and Barcelona. Madrid is located in the continental zone and has more than 3 million residents, while Barcelona is in the Mediterranean zone and has more than 1.5 million. They quadruple or double, respectively, the number of residents of the third most populated city of Spain. For this reason, their energy consumption is so high that it increases the standard deviations of both climate zones when considering global values.

Most cities in Spain are placed in areas with continental and Mediterranean climates, reaching 75% in the case of this study's sample. Despite the fact that the whole area with continental climate in Spanish territory is greater than the area with Mediterranean climate, the total amount of cities in both climate zones is very similar. The number of cities in the semi-arid and subtropical regions is small since they are very specific zones, limited to the south-east of the Iberian Peninsula and the Canary Islands (Fig. 3).

Fig. 3 Number of cities by type of climate

Table 2 shows the main statistical data of the 145 cities of this study's sample. They are grouped in the five climate zones of Spain. Data of the continental zone without Madrid and the Mediterranean zone without Barcelona are also showed in the table. Note the influence that these two cities have on the total values of both climate zones, as well as the reduction in the standard deviations. Just as with the number of cities located in each climate zone and despite the area of land of the continental climate zone, the population that lives in cities with Mediterranean climate is proportionally greater than the population that lives in cities with continental climate. Regarding cities mean size, those with continental climate are the biggest ones, followed by the ones with semi-arid climate. These last ones are located in a small area, although they have a great number of residents. As for the number of inhabitants per household, houses in the semi-arid climate zone present the biggest amount of them, followed by those in the subtropical region. However, households from all climate zones present similar numbers of inhabitants, except for the houses in the oceanic climate zone.

Total energy consumption

Table 3 shows the statistical data of cities total consumption, in MWh per year, of each climate zone. They are separated in thermal and electric energy consumption. This table also presents the continental zone without Madrid, as well as the Mediterranean zone without Barcelona. Values can be observed without these two big cities, since they double at least the size (in terms of number of inhabitants) of the third biggest city of Spain. Thermal energy consumption in the semi-arid and subtropical zones is little, and in the Mediterranean zone is not high, whereas the areas of greatest consumption are firstly the continental zone and then the oceanic one. Nevertheless, the situation changes radically in the matter of electric energy consumption. The mean energy consumption in the semi-arid zone is nearly the same as the one in the continental zone. It even exceeds it if Madrid's impact is not considered. Next come electricity consumptions of the Mediterranean zone followed by the subtropical zone. They surpass consumptions of the oceanic climate region. This is due to a bigger thermal energy consumption for heating observed in cold places during the winter. This type of consumption barely exists in warm areas or in those where winters are gentler. On the contrary, the electric energy consumption for air conditioning during the summer is higher in warm areas, as well as in areas that have a great thermal range with extreme temperatures. Therefore, the electricity use in these areas is high. Besides, in these zones air conditioners are not only used for cooling, but also for heating during some cold winter days. For this reason, they replace the thermal energy consumption of other climate regions.

Cities total energy consumption is presented in Fig. 4 and 5 with the aim of analysing their tendency. Those with similar scales have been grouped for a better evaluation: on the one hand, the continental and Mediterranean climates; on the other hand, the oceanic, semi-arid and subtropical climates. In every case it is observed that the tendency of the cities total consumption values can be adjusted with a polynomial curve. The coefficients of determination R^2 are shown in Table 4. Their values are greater than 0.98 in every case, except for the oceanic climate zone, whose values are higher than 0.94. The curve that corresponds to the continental climate is overall above the Mediterranean

Table 2 Statistical data of climate zones by population and households

	POPULATION						NUMBER OF HOUSEHOLDS					
CLIMA	**Total**	**Mean**	**Std. dev.**	**Median**	**Maximum**	**Minimum**	**Total**	**Mean**	**Std. dev.**	**Median**	**Maximum**	**Minimum**
Continental	10,930,682	188,460	418,055	95,494	3,182,981	50,442	4,200,427	72,421	166,088	35,176	1,262,282	15,434
Continental (without Madrid)	7,747,701	135,925	122,285	95,071	689,434	50,442	2,938,145	51,546	48,504	33,149	269,347	15,434
Mediterranean	7,960,213	159,204	249,177	82,645	1,620,809	50,334	3,040,127	60,803	101,186	29,441	666,143	18,541
Mediterranean (without Barcelona)	6,339,404	129,376	134,046	82,142	787,808	50,334	2,373,984	48,449	51,595	29,263	312,339	18,541
Oceanic	2,501,771	147,163	95,338	97,995	345,110	51,776	1,030,041	60,591	39,752	40,928	144,755	20,632
Semi-arid	1,967,543	163,962	122,300	92,831	443,243	52,620	714,104	59,509	44,301	34,132	154,421	20,418
Subtropical	1,099,641	137,455	109,934	90,468	377,650	53,542	409,770	51,221	40,514	34,256	138,191	20,913

Table 3 Statistical data of consumption by climate zones

	TOTAL (MWh/year)					THERMAL (MWh/year)					ELECTRIC (MWh/year)				
CLIMATE	**Mean**	**Std. dev.**	**Median**	**Maximum**	**Minimum**	**Mean**	**Std. dev.**	**Median**	**Maximum**	**Minimum**	**Mean**	**Std. dev.**	**Median**	**Maximum**	**Minimum**
Continental	955,845	2,400,524	465,090	18,400,465	140,786	420,925	1,177,868	204,700	8,969,965	14,287	534,920	1,233,652	265,211	9,430,500	123,033
Continental (without	649,799	579,560	450,302	3,717,939	140,786	270,942	290,072	200,928	1,627,614	14,287	378,857	333,503	256,895	2,090,324	123,033
Mediterranean	627,277	1,139,465	299,825	7,756,365	143,830	198,247	492,539	87,294	3,447,946	0	429,031	675,886	203,870	4,308,420	135,908
Mediterranean (without	481,786	494,965	293,872	2,805,385	143,830	131,926	152,143	65,824	643,146	0	349,859	382,630	203,434	2,162,239	135,908
Oceanic	595,584	390,330	360,657	1,488,023	214,157	228,256	182,236	156,441	648,985	54,936	367,327	233,925	280,179	839,038	120,861
Semi-arid	533,031	421,006	296,613	1,516,830	175,312	54,336	50,679	28,752	175,951	12,317	478,696	371,523	263,504	1,340,879	156,617
Subtropical	373,099	316,572	252,063	1,104,302	156,564	0	0	0	1	0	373,099	316,571	252,062	1,104,301	156,564

Fig. 4 Total consumption of cities with continental and Mediterranean climates

Fig. 5 Total consumption of cities with oceanic, semi-arid and subtropical climates

Table 4 Coefficients of determination R^2 of each type of climate

CLIMATE	**R^2**
Continental	0.9875
Mediterranean	0.9836
Oceanic	0.9403
Semi-arid	0.9918
Subtropical	0.9962

climate one, followed by the oceanic, semi-arid and tropical climates curves in descending order. This gives a global idea of how consumptions are.

Energy consumptions per household

The analysis of consumptions per household, in MWh per year, of each climate zone can be observed in Table 5 and Fig. 6. Table 5 shows the main statistical parameters. It was not necessary to include the results without Madrid and Barcelona in this case, as they are mean values per household. The highest mean consumption is noticed in the continental zone, where climate is extremer. The Mediterranean and oceanic climate zones show similar energy consumptions. The subtropical climate region is the one with the lowest total consumption per household. In addition, the only climate zone with consumptions higher than the national mean is the continental one. It presents an energy use of almost 20%. When examining the thermal energy consumption, the continental zone presents the highest consumption. There, the energy use is more than 40% higher than consumption in the oceanic region, which is the second area that has the highest consumptions. These two climate zones are the only ones that surpass the national mean. Besides, energy consumption in the Mediterranean climate zone is nearly 25% lower than consumption in the oceanic zone, being the Mediterranean climate zone the third one of highest thermal energy uses. Meanwhile consumptions in the semi-arid and subtropical zones are close to zero. In other words, thermal energy consumptions in each climate zone are considerably disparate. Nevertheless, the situation changes drastically when analysing the electric energy use: the semi-arid climate zone presents the highest consumption (8% higher than the mean, approximately), while the oceanic region has the lowest one (nearly 15% less than the mean). Electric energy consumption is similar in the other three climate zones. As for the conclusions, they are much the same as the ones drawn regarding cities consumptions, although they are not identical. The influence of climate on consumption habits is once again noticed: the total energy consumption is higher or lower depending on weather conditions (rough or smooth weather), and most of the energy consumed is thermal or electric depending on which the severest season is (winter or summer, respectively). This is due to the fact that the thermal energy is used for heating, while electricity is used for air conditioning. However, the electric energy is also used for heating, particularly in places where winters are gentler. In every case it is important to take into account that there is a base electricity consumption corresponding to electrical appliances, as well as to electrical and electronic devices. All of them are always in every home.

Table 5 Statistical data of household consumption by climate zones

	TOTAL (MWh/year)					THERMAL (MWh/year)					ELECTRIC (MWh/year)				
CLIMATE	**Mean**	**Std. dev.**	**Median**	**Maximum**	**Minimum**	**Mean**	**Std. dev.**	**Median**	**Maximum**	**Minimum**	**Mean**	**Std. dev.**	**Median**	**Maximum**	**Minimum**
Continental	12.94	3.79	13.83	18.79	6.89	5.37	3.03	6.25	9.16	0.65	7.57	1.15	7.81	9.64	5.67
Mediterranean	9.88	2.70	9.54	14.36	5.66	2.88	2.33	2.08	6.38	0.00	7.00	0.81	7.00	9.46	5.66
Oceanic	9.85	1.30	9.96	12.36	7.55	3.77	1.53	4.44	6.07	1.69	6.08	0.61	5.86	7.49	5.30
Semi-arid	8.69	0.99	8.43	10.23	7.24	0.85	0.30	0.90	1.19	0.37	7.84	0.74	7.60	9.05	6.87
Subtropical	7.25	0.99	7.46	8.33	5.99	0.00	0.00	0.00	0.00	0.00	7.25	0.99	7.46	8.33	5.99

Fig. 6 Thermal, electric and total energy consumption per household by climate zones

The CVI index previously defined was used to analyse the consumption variations observed in each climate zone. Fig. 7-9 show the mean, minimum and maximum CVI index values for households total energy consumptions, thermal energy consumptions and electric energy consumptions by climate zones, respectively. The mean value represents the mean performance of each climate region, while the maximum and minimum values symbolise the maximal deviations of each of these regions in comparison with their mean value. This is presented in three different figures for a better understanding.

As seen in these three figures, maximal deviations are observed in areas with a larger number of cities, and they decrease as this number drops. This coincides with regions that are geographically wider and that have, therefore, a higher dispersion regarding weather conditions. The reason is that, although they share similar weathers, it always exits a variation range within each climate. Consequently, the difference between the maximum and minimum CVI decreases from the continental to the subtropical zone. With regard to the total CVI index, it is observed that its mean value is alike in the Mediterranean and oceanic climates. This value can vary between 0.7 in the subtropical zone and 1.2 in the continental one.

Fig. 8 presents the thermal energy consumption index. As seen in the figure, a great variability exits between the different climate zones. Its mean value varies between 0 in the case of the subtropical climate and 1.5 for the continental one. It is also observed that the variation between the maximum and minimum values in the continental climate is noteworthy due to the high disparity of cities with this type of climate. However, performances are fully similar in cities located in the semi-arid and subtropical areas, where thermal energy consumption barely exits. Finally, as noticed in Fig. 9 electricity consumptions in every climate zone have similar dispersions between the maximum and minimum values. And their mean values vary between 0.8 and 1.1. As presented in Fig. 6, the semi-arid climate zone is the one with the highest energy consumption. In addition, it can be observed that there is a minimum value for the electric energy use of every house regardless of the climate zone where it is located. The rest of conclusions drawn from these figures are the same as the ones explained for Fig. 6.

Fig. 7 Variation of the CVI index for the total energy consumption per household by climate zone

Fig. 8 Variation of the CVI index for the thermal energy consumption per household by climate zone

Fig. 9 Variation of the CVI index for the electric energy consumption per household by climate zone

Energy consumptions per inhabitant

Table 6 and Fig. 10 are presented with the aim of analysing energy consumption per inhabitant, in MWh per year, of each climate zone. Table 6 shows the basic statistical data. Performance of energy consumptions per inhabitant is in general like performance of consumptions per household, although values are different: consumption is higher in zones with extremer climates than in zones with gentler weathers; thermal energy consumption is higher in regions where the use of heating is greater during the winter; and electricity consumption is more significant in warmer areas.

Fig. 10 Thermal, electric and total energy consumption per inhabitant in each climate zone

The CVI index was used to analyse the consumption variations observed in each climate zone. Fig. 11-13 present the mean, the minimum and the maximum CVI index values for the total, thermal and electric energy consumptions per inhabitant in each climate zone, respectively. Conclusions drawn when examining these figures are similar to the ones previously explained for the index per household: maximal deviations are observed in regions with a higher number of cities and they decrease as this number drops; regarding the thermal energy consumption (Fig. 12), an important variability is observed between climate zones and especially between the maximum and minimum values of the continental climate; cities located in the semi-arid and subtropical areas with a scarce thermal energy consumption present similar performances; electric CVI maximum and minimum values share similar deviations, and the semi-arid climate zone has a clear leadership in consumption; a minimum value of electricity consumption per inhabitant is observed, independent of the climate zone it belongs to. The rest of conclusions drawn from these figures are the same as the ones previously mentioned for Fig. 10.

Table 6 Statistical data of consumption per inhabitant of each climate zone

	TOTAL (MWh/year)					THERMAL (MWh/year)					ELECTRIC (MWh/year)				
CLIMATE	Mean	Std. dev.	Median	Maximum	Minimum	Mean	Std. dev.	Median	Maximum	Minimum	Mean	Std. dev.	Median	Maximum	Minimum
Continental	4.83	1.25	5.59	6.47	2.67	2.00	1.09	2.46	3.76	0.24	2.83	0.31	2.96	3.86	2.26
Mediterranean	3.74	1.03	3.56	4.79	1.67	1.09	0.87	0.82	2.13	0.00	2.65	0.36	2.66	3.57	1.67
Oceanic	4.07	0.53	4.30	4.95	3.07	1.56	0.63	1.88	2.43	0.69	2.51	0.24	2.43	2.93	2.32
Semi-arid	3.21	0.30	3.33	3.42	2.71	0.32	0.11	0.36	0.40	0.14	2.89	0.19	2.98	3.03	2.57
Subtropical	2.73	0.27	2.92	2.92	2.40	0.00	0.00	0.00	0.00	0.00	2.73	0.27	2.92	2.92	2.40

Fig. 11 Variation of the CVI index for the total energy consumption per inhabitant by climate zone

Fig. 12 Variation of the CVI index for the thermal energy consumption per inhabitant by climate zone

Fig. 13 Variation of the CVI index for the electric energy consumption per inhabitant by climate zone

CO_2 emissions

Once being familiar with the thermal and electric energy consumptions of each climate zone, CO_2 emissions values can be obtained basing on the values set by the Spanish government: 0.252 tCO_2/MWh for natural gas consumption and 0.291 tCO_2/MWh for electricity consumption. Fig. 14 shows CO_2 emissions per household by climate zone and their mean values (for the total, thermal or electric energy consumptions). Fig. 15 shows these emissions per inhabitant. Conclusions are similar to the ones drawn in "Energy consumptions per household" and "Energy consumptions per inhabitant" sections, since CO_2 emissions are proportional to consumptions in each climate zone.

The greatest emissions per household are produced in the continental zone. They are 18% over the mean in this zone. Emissions of the rest of climate zones are under the mean value. Emissions of the Mediterranean and oceanic zones come next, and they share similar values. The subtropical zone presents the lowest CO_2 emissions. With regard to the emissions caused by the thermal energy, the greatest amount of them is observed in the continental zone. The oceanic zone comes next. Both climate zones present values higher than the mean. Emissions in the semiarid zone are minute and they are zero in the subtropical one. However, when analysing the highest emissions caused by electric energy, it is observed that most of them are produced in the semiarid climate zone followed by the continental one. The Mediterranean and oceanic zones present values under the mean. In particular, values of emissions in the oceanic zone are 15% lower than the mean. And in every case, the electric energy is responsible for emissions that vary between 62% (continental climate) and 100% (subtropical climate) of the total emissions within each climate zone.

Similar performances are observed when analysing emissions per inhabitant. The continental climate zone shows the highest emissions values. This zone is also the only one whose values are over the national mean. Its CO_2 emissions caused by thermal energy are nearly 45% higher than the mean. Emissions in the subtropical and semiarid climate zones are the opposite. The subtropical zone produces the lowest values of CO_2 emissions, as well as zero thermal emissions. As for the semiarid zone, it presents emissions 77% under the mean. However, this last climate zone is where the highest emissions caused by electric energy are produced. Regarding the emissions percentage produced by electric energy within each climate zone, it is observed once again that the continental zone presents the smallest percentage and that it is higher than 60%. In the case of the subtropical climate zone, this percentage reaches 100%.

The conclusions drawn from the CO_2 emissions are: climate zones with higher consumptions produce higher emissions; climate zones with severe climates produce higher emissions; in every case, electric energy is responsible for the highest emissions percentage compared to the total emissions within a climate zone, and this percentage varies from 62% to 100%.

Fig. 14 Thermal, electric and total CO_2 emissions per household by climate zones

Fig. 15 Thermal, electric and total CO_2 emissions per inhabitant in each climate zone

Conclusions

Cities are one of the key points within a country where to take actions with the aim of getting faster results. It is important to take into account that more than half of the world population live in the cities, reaching 70% in Europe. In particular, in Spain more than half of the population live in cities with more than 50,000 inhabitants. Moreover, Spain is one of the countries where less studies regarding cities performance from the energetic and climate points of view have been carried out.

In this paper the 145 Spanish cities with more than 50,000 inhabitants were identified, the different types of climate of this country were analysed and each and one of these 145 cities were classified based on their climate. Then, thermal and electric energy consumption of the five different climate zones defined in Spain were analysed. This study was carried out from the point of view of cities, households and inhabitants, analysing dissimilarities in consumption and explaining possible reasons. Furthermore, an index was defined to facilitate this analysis. Cities with extremer climates present a higher energy consumption in contrast to those located in milder climate zones; depending on which the severest season is (winter or summer), thermal or electric energy consumption is the highest one, respectively, since the thermal energy consumption is basically used for heating; the electricity use is more important in warmer zones, as it is used for both air conditioning and heating in regions with gentler winters; and in every case it must be taken into consideration that electrical devices together with electrical and electronic equipment are responsible for a base electricity consumption that always exists in every home. Finally, CO_2 emissions of each climate zone were calculated, which give an idea of the renewable installations that are needed to eliminate these pollutant emissions. In every zone, electric energy is responsible for emissions that are greater than 60%. And they reach 100% depending on the climate zone.

Acknowledgments

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

Agencia Estatal de Meteorología (2018) Mapas climáticos de España (1981-2010) y ETo (1996-2016). Madrid: Ministerio para la Transición Ecológica

Al-Zayer J, Al-Ibrahim A (1996) Modelling the impact of temperature on electricity consumption in the eastern province of Saudi Arabia. J Forecast 15:97-106. https://doi.org/10.1002/(SICI)1099-131X(199603)15:2<97::AID-FOR608>3.0.CO;2-L

Alcántara V, Padilla E (2009) Input-output subsystems and pollution: An application to the service sector and CO_2 emissions in Spain. Ecol Econ 68(3):905-914. https://doi.org/10.1016/j.ecolecon.2008.07.010

Ashouri JA, Rafei M (2018) Analysis of asymmetries in air pollution with water resources, and energy consumption in Iran. Environ Sci Pollut Res 25:17590-17601. https://doi.org/10.1007/s11356-018-1825-5

Balcilar M, Bekun FV, Uzuner G (2019) Revisiting the economic growth and electricity consumption nexus in Pakistan. Environ Sci Pollut Res 26:12158-12170. https://doi.org/10.1007/s11356-019-04598-0

Bessec M, Fouquau J. (2008) The non-linear link between electricity consumption and temperature in Europe: A threshold panel approach. Energy Econ 30:2705-2721. https://doi.org/10.1016/j.eneco.2008.02.003

Cancelo JR, Espasa A, Grafe R (2008) Forecasting the electricity load from one day to one week ahead for the Spanish system operator. J Forecast 24:588-602. https://doi.org/10.1016/j.ijforecast.2008.07.005

Chen Q, Bofeng C, Dhakal S, Pei S, Liu C, Shi X, Hu F (2017) CO_2 emission data for Chinese cities. Resour Conserv Recycl 126:198-208. http://doi.org/10.1016/j.resconrec.2017.07.011

Comisión Nacional de los Mercados y la Competencia (2017) Informe de supervisión del mercado de gas natural en España. Madrid: Ministerio de Economía, Industria y Competitividad

Committed to local sustainable energy, Reducing energy dependence in European cities, Covenant of Mayors (2018). http://www.soglasheniemerov.eu/IMG/pdf/CoM_Reducing_Energy_Dependence_for_web_eng.pdf Accessed 11 December 2018

Danish, Saud S, Baloch MA, Lodhi RN (2018) The nexus between energy consumption and financial development: estimating the role of globalization in Next-11 countries. Environ Sci Pollut Res 25:18651-18661. https://doi.org/10.1007/s11356-018-2069-0

Department of Economic and Social Affairs (2015) 2014 Demographic yearbook. (Sixty-fourth ed.). New York: United Nations

Eurostat Methodologies and Working Papers (2008) Statistical classification of economic activities in the European Community. Luxembourg.

Fang C, Wang S, Li G (2015) Changing urban forms and carbon dioxide emissions in China: A case study of 30 provincial capital cities. Appl Energy 158:519-531. http://doi.org/10.1016/j.apenergy.2015.08.095

Gurney KR, Razlivanov I, Song Y, Zhou Y, Benes B, Abdul-Massih M (2012) Quantification of fossil fuel CO_2 emissions on the building/street scale for a large US city. Environ Sci Technol 46(21):12194-12202. http://doi.org/10.1021/es3011282

Guriérrez R, Gutiérrez-Sánchez R, Nafidi A, Ramos E (2007) A diffusion model with cubic drift: statistical and computational aspects and application to modelling of the global CO_2 emission in Spain. Environmetrics 18:55-69. http://doi.org/10.1002/env. 801

Hekkenberg M, Benders RMJ, Moll HC, Schoot AJM (2009) Indications for a changing electricity demand pattern: The temperature dependence of electricity demand in the Netherlands. Energy Policy 37:1542-1551. https://doi.org/10.1016/j.enpol.2008.12.030

Ihara T, Genchi Y, Sato T, Yamaguchi K, Endo Y (2008) City-block-scale sensitivity of electricity consumption to air temperature and air humidity in business districts of Tokyo, Japan. Energy 33:1634-1645. https://doi.org/10.1016/j.energy.2008.06.005

Instituto Geográfico Nacional, Tipos de clima, Ministerio de Fomento (2018) https://www.ign.es/espmap/mapas_clima_bach/pdf/Clima_Mapa_13texto.pdf Accessed 3 October 2018

Instituto Nacional de Estadística, Cifras de población, Ministerio de Economía, Industria y Competitividad (2018 a) http://www.ine.es/dyngs/INEbase/es/operacion.htm?c=Estadistica_C&cid=1254736176951&menu=ultiDatos&idp=1254735572981 Accessed 11 October 2018

Instituto Nacional de Estadística, Demografía y población, Ministerio de Economía, Industria y Competitividad (2018 b) http://www.ine.es/ss/Satellite?L=es_ES&c=Page&cid=1254735910183&p=1254735910183&pagename=INE%2FINELayout Accessed 10 October 2018

Izquierdo M, Moreno-Rodríguez, A, González-Gil A, García-Hernando N (2011) Air conditioning in the region of Madrid, Spain: An approach to electricity consumption, economics and CO_2 emissions. Energy 36:1630-1639. https://doi.org/10.1016/j.energy.2010.12.068

Li DHW, Yang L, Lam JC (2012) Impact of climate change on energy use in the built environment in different climate zones – A review. Energy 42:103-112. https://doi.org/10.1016/j.energy.2012.03.044

Liu X (2018) Aggregate and disaggregate analysis on energy consumption and economic growth nexus in China. Environ Sci Pollut Res 25:26512-26526. https://doi.org/10.1007/s11356-018-2699-2

Makido Y, Dhakal S, Yamagata Y (2012) Relationship between urban form and CO_2 emissions: Evidence from fifty Japanese cities. Urban Clim 2:55-67. http://doi.org/10.1016/j.uclim.2012.10.006

Ministerio de Industria, Energía y Turismo, Ministerio de Fomento (2016) Factores de emisión de CO_2 y coeficientes de paso a energía primaria de diferentes fuentes de energía final consumidas en el sector de edificios de España. https://energia.gob.es/desarrollo/EficienciaEnergetica/RITE/Reconocidos/Paginas/IndexDocumentosReconocidos.aspx Accessed 21 October 2018

Mirasgedis S, Sarafidis Y, Georgopoulou E, Kotroni V, Lagouvardos K, Lalas DP (2007) Modeling framework for estimating impacts of climate change on electricity demand at regional level: Case of Greece. Energy Convers Manag 48:1737-1750. https://doi.org/10.1016/j.enconman.2006.10.022

Moral-Carcedo J, Vicéns-Otero J (2005) Modelling the non-linear response of Spanish electricity demand to temperature variations. Energy Econ 27:477-494. https://doi.org/10.1016/j.enco.2005.01.003

Nasr GE, Badr EA, Younes MR (2002) Neural networks in forecasting electrical energy consumption: univariate and multivariate approaches. Int J Energy Res 26:67-78. https://doi.org/10.1002/er.766.abs

Nasreen S, Saidi S, Ozturk I (2018) Assessing links between energy consumption, freight transport, and economic growth: evidence from dynamic simultaneous equation models. Environ Sci Pollut Res 25:16825-16841. https://doi.org/10.1007/s11356-018-1760-5

Oxford Living Dictionaries. (2019). https://en.oxforddictionaries.com/definition/climate Accessed 5 February 2019

Ozturk I (2015) Measuring the impact of energy consumption and air quality indicators on climate change: evidence from the panel of UNFCC classified countries. Environ Sci Pollut Res 22:15459-15468. https://doi.org/10.1007/s11356-015-4757-3

Pardo A, Meneu V, Valor E (2002) Temperature and seasonality influences on Spanish electricity load. Energy Econ 24:55-70. https://doi.org/10.1016/S0140-9883(01)00082-2

Pilli-Sihvola K, Aatola P, Ollikainen M, Tuomenvirta H (2010) Climate change and electricity consumption – Witnessing increasing or decreasing use and costs?. Energy Policy 38:2409-2419. https://doi.org/10.1016/j.enpol.2009.12.033

Sailor D, Muñoz JR (1997) Sensitivity of electricity and natural gas consumption to climate in the U.S.A. – Methodology and results for eight states. Energy 22(10):987-998. https://doi.org/10.1016/S0360-5442(97)00034-0

Sailor D, Rosen J, Muñoz JR (1998) Natural gas consumption and climate: A comprehensive set of predictive state-level models for the United States. Energy 23(2):91-103. https://doi.org/10.1016/S0360-5442(97)00073-X

Sánchez-Úbeda EF, Berzosa A (2007) Modelling and forecasting industrial end-use natural gas consumption. Energy Econ 29:710-742. https://doi.org/10.1016/j.eneco.2007.01.015

Santamouris M, Cartalis C, Synnefa A, Kolokotsa D (2015) On the impact of urban heat island and global warming on the power demand and electricity consumption of buildings – A review. Energy Build 98:119-124. https://doi.org/10.1016/j.enbuild.2014.09.052

Sarak H, Satman A (2003) The degree-day method to estimate the residential heating natural gas consumption in Turkey: A case study. Energy 28:929-939. https://doi.org/10.1016/S0360-5442(03)00035-5

Secretaría de Estado de la Energía (2018) Estadísticas y balances energéticos. Madrid: Ministerio para la Transición Ecológica

Shahrokni H, Levihn F, Brandt N (2014) Big meter data analysis of the energy efficiency potential in Stockholm's building stock. Energy Build 78:153-164. https://doi.org/10.1016/j.enbuild.2014.04.017

Shan Y, Guan D, Liu J, Mi Z, Liu Z, Liu J, Schroeder H, Cai B, Chen Y, Shao S, Zhang Q (2017) Methodology and applications of city level CO_2 emissions accounts in China. J Clean Prod 161:1215-1225. http://doi.org/10.1016/j.jclepro.2017.06.075

Szoplik J (2015) Forecasting natural gas consumption with artificial neural networks. Energy 85:208-220. https://doi.org/10.1016/j.energy.2015.03.084

Taspinar F, Celebi N, Tutkun N (2013) Forecasting of daily natural gas consumption on regional basis in Turkey using various computational methods. Energy Build 56:23-31. https://doi.org/10.1016/j.enbuild.2012.10.023

Urquizo J, Calderón C, James P (2017) Metrics of urban morphology and their impact on energy consumption: A case study in the United Kingdom. Energy Res Soc Sci 32:193-206. https://doi.org/10.1016/j.erss.2017.03.011

Valor E, Meneu V, Caselles V (2001) Daily air temperature and electricity load in Spain. Appl Meteorol 40:1413-1421. https://doi.org/10.1175/1520-0450(2001)040<1413:DATAEL>2.0.CO;2

Wang H, Zhang R, Liu M, Bi J (2012) The carbon emissions of Chinese cities. Atmos Chem Phys 12:6197-6206. http://doi.org/10.5194/acp-12-6197-2012

Wang S, Xiaoping L (2017) China's city-level energy-related CO_2 emissions: Spatiotemporal patterns and driving forces. Appl Energy 220:204-214. http://doi.org/10.1016/j.apenergy.2017.05.085

Wangpattarapong K, Maneewan S, Ketjoy N, Rakwichian W (2008) The impacts of climatic and economic factors on residential electricity consumption of Bangkok Metropolis. Energy Build 40:1419-1425. https://doi.org/10.1016/j.enbuild.2008.01.006

Yu W, Pagani R, Huang L (2012) CO_2 emission inventories for Chinese cities in highly urbanized areas compared with European cities. Energy Policy 47:298-308. https://doi.org/10.1016/j.enpol.2012.04.071

Zhong X, Jiang H, Zhang C, Shi R (2019) Electricity consumption and economic growth nexus in China: an autoregressive distributed lag approach. Environ Sci Pollut Res 26:14627-14637. https://doi.org/10.1007/s11356-019-04699-w

Zhou Y, Shan Y, Guosheng L, Guan D (2018) Emissions and low-carbon development in Guaandong-Hong Kong-Macao Greater Bay Area cities and their surroundings. Appl Energy 228:1683-1692. https://doi.org/10.1016/j.apenergy.2018.07.038

Influence of climate on energy consumption and CO_2 emissions: the case of Spain

Irene M. Zarco-Soto [a], Pedro J. Zarco-Periñán [a,*], Rafael Sánchez-Durán [b]

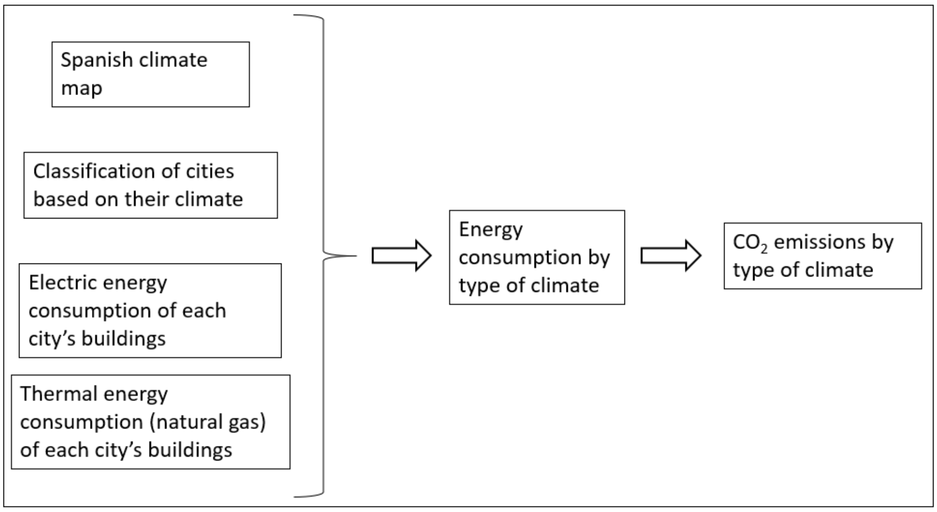
[*] *E-mail address:* pzarco@us.es

[a] *Departamento de Ingeniería Eléctrica, Escuela Superior de Ingeniería, Universidad de Sevilla, Camino de los Descubrimientos, s/n, 41092 Sevilla, Spain*

[b] *Endesa, Avenida de la Borbolla, 5, 41004, Sevilla, Spain*

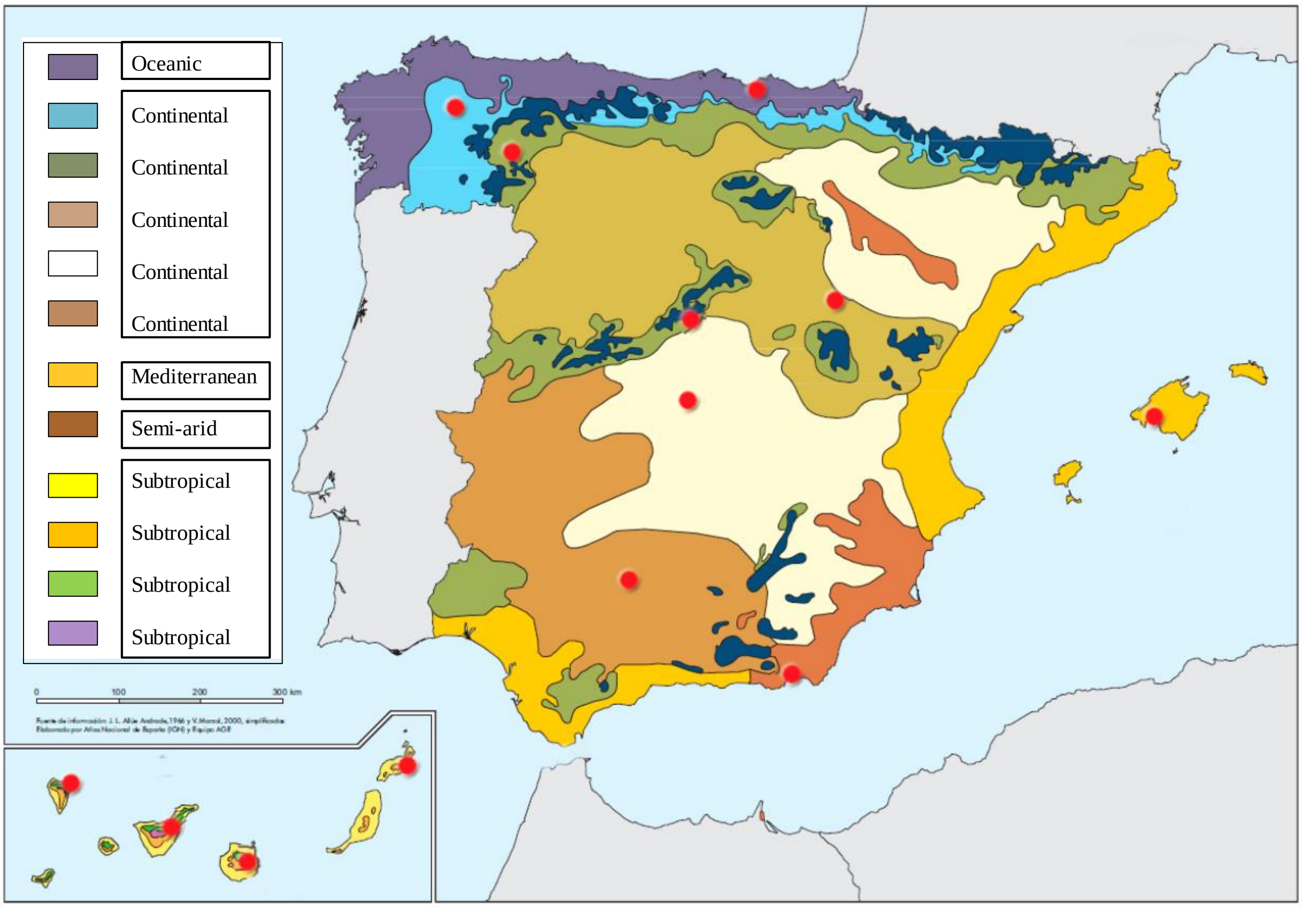
Conflict of interest: The authors declare that they have no conflict of interest.

Acknowledgements: This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.



Spanish climate map
Classification of cities based on their climate
Electric energy consumption of each city's buildings
Thermal energy consumption (natural gas) of each city's buildings
Energy consumption by type of climate
CO_2 emissions by type of climate

Fig. 1



Oceanic
Continental
Continental
Continental
Continental
Continental
Mediterranean
Semi-arid
Subtropical
Subtropical
Subtropical
Subtropical
0
100
200
300 km

Fig. 2

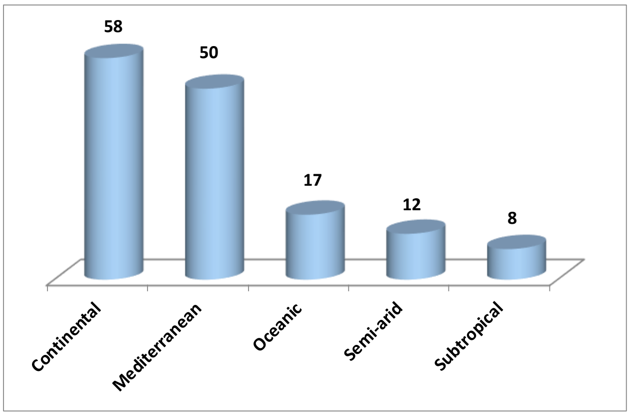


Fig. 3

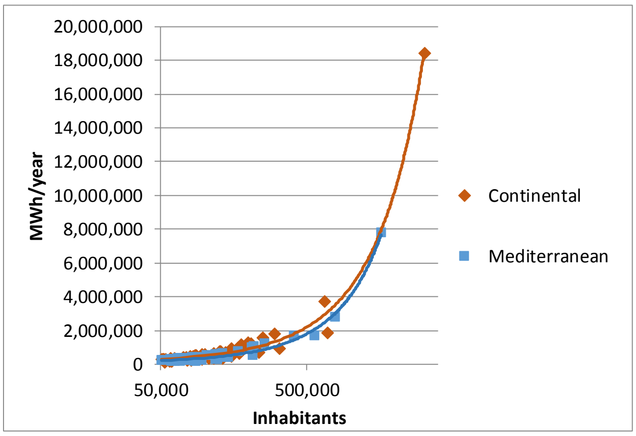


Fig. 4

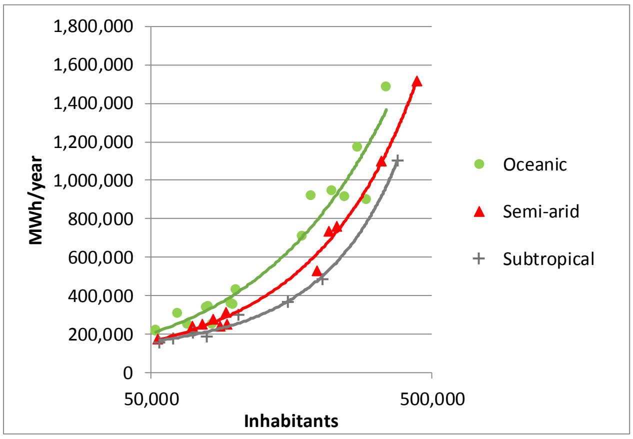


Fig. 5

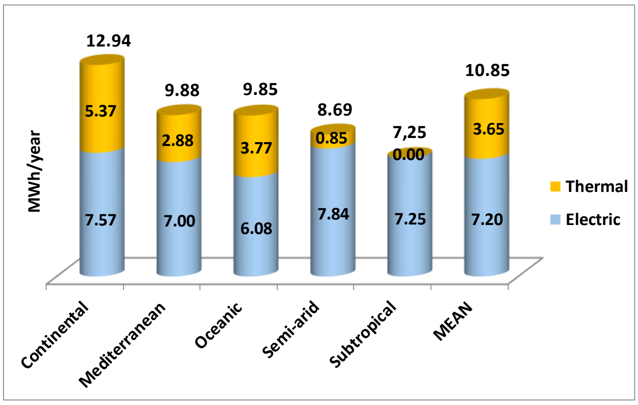


Fig. 6

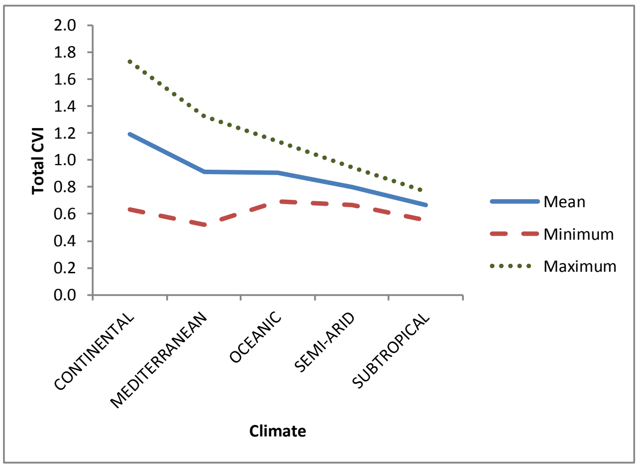


Fig. 7

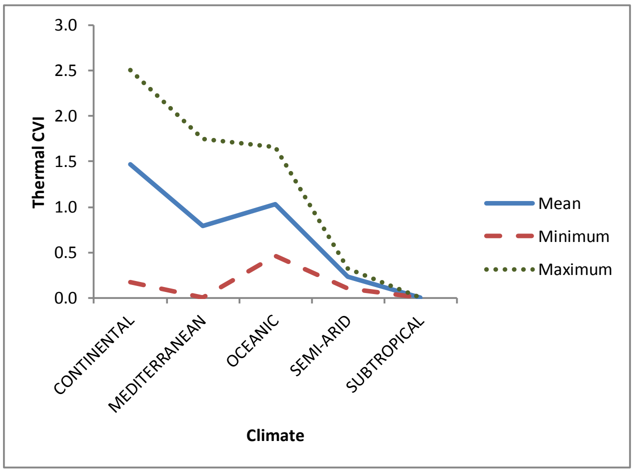


Fig. 8

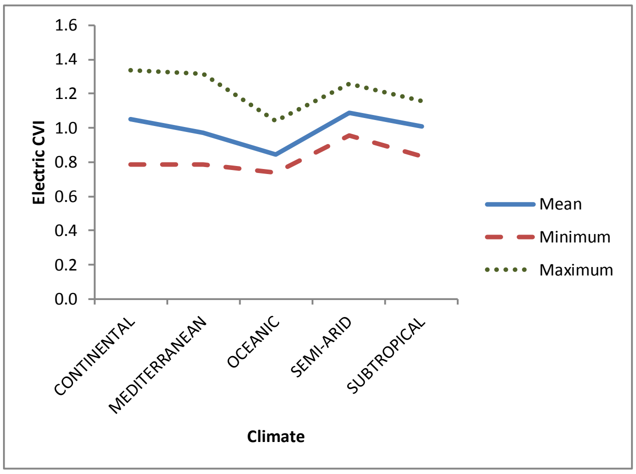


Fig. 9

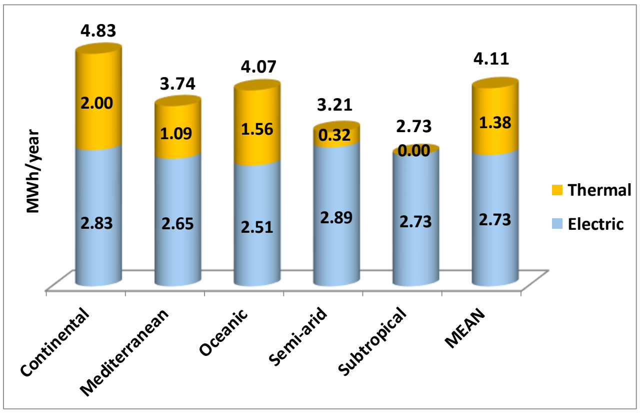


Fig. 10

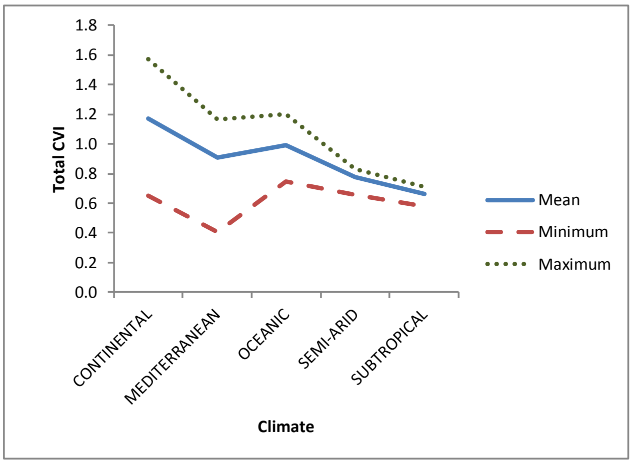


Fig. 11

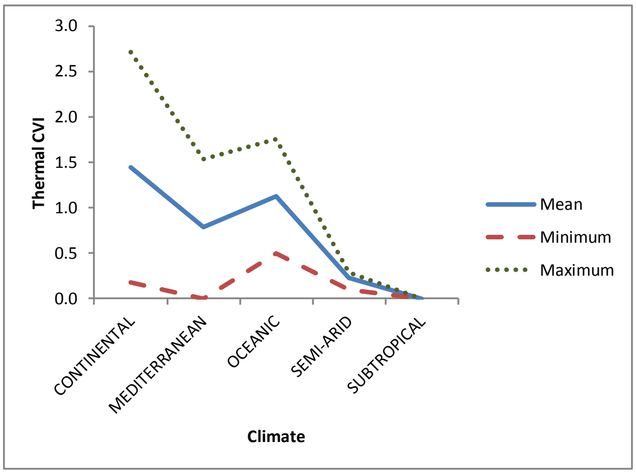


Fig. 12

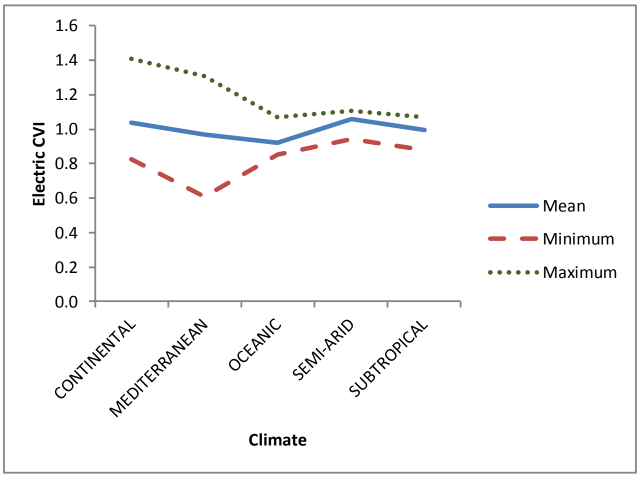


Fig. 13

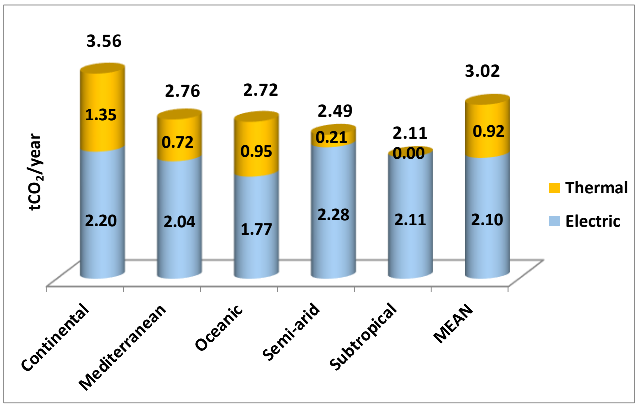


Fig. 14

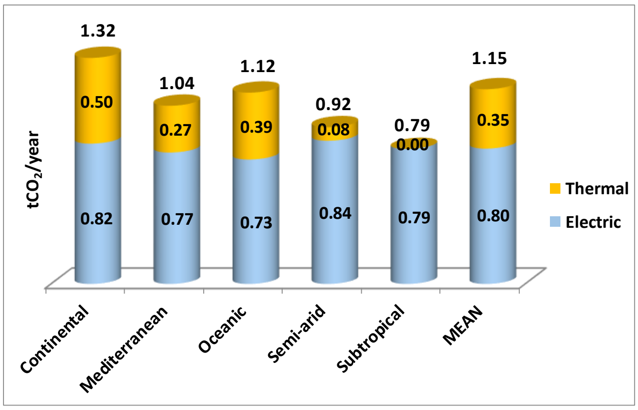

1.32
1.04
1.12
0.92
0.79
1.15
0.50
0.27
0.39
0.08
0.00
0.35
0.82
0.77
0.73
0.84
0.79
0.80
tCO2/year
Thermal
Electric
Continental
Mediterranean
Oceanic
Semi-arid
Subtropical
MEAN

Fig. 15

Cover letter

Click here to access/download

Supplementary Material

Cover letter_Climate, energy consumption and emissions.pdf